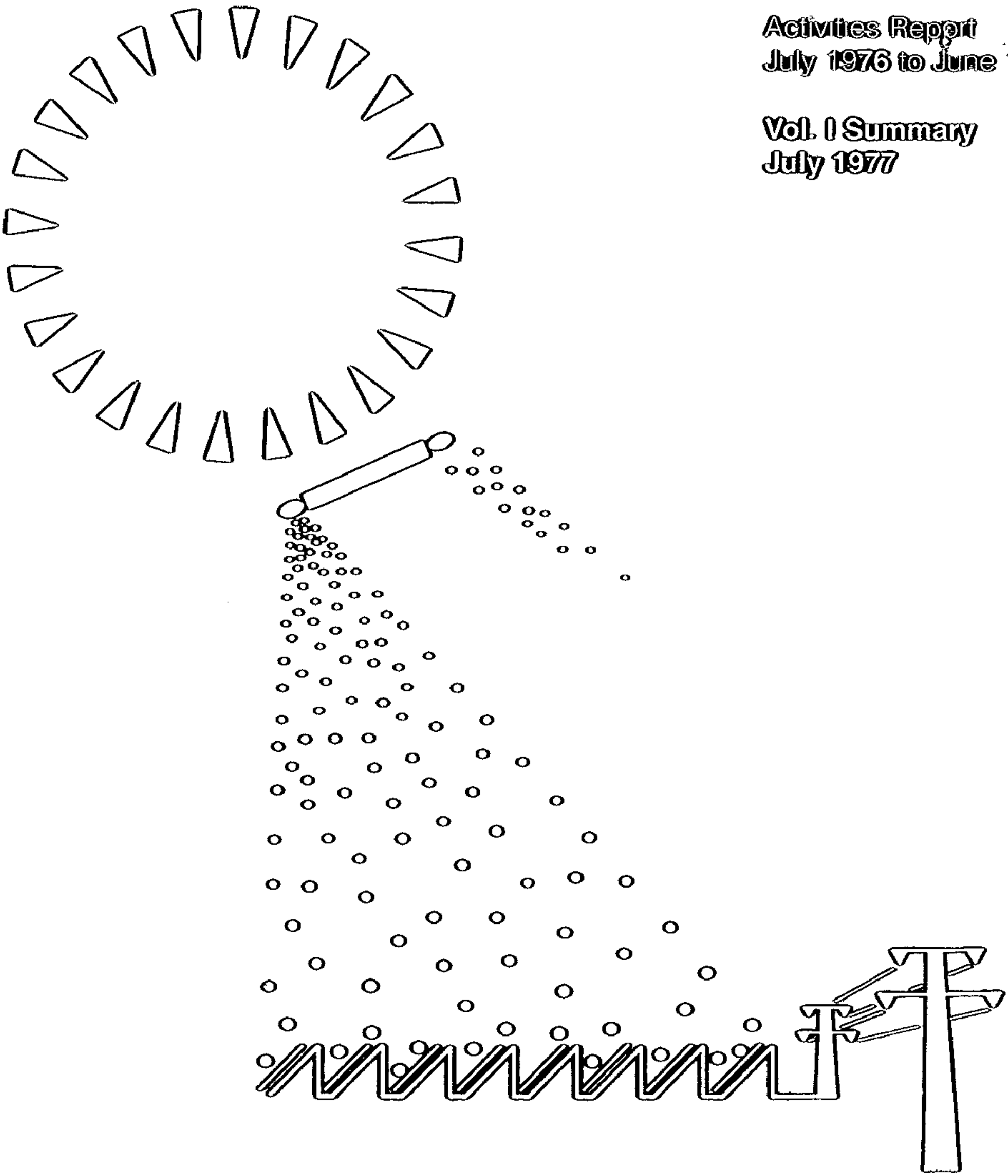
NASA Solar Power Satellite

Concept Evaluation

Activities Report
July 1976 to June 1977

Vol. I Summary
July 1977



(NASA-TM-74820) SOLAR POWER SATELLITE CONCEPT EVALUATION. VOLUME 1: SUMMARY Progress Report, Jul. 1976 - Jun. 1977 (NASA) 130 p HC A07/MF A01 CSCL 10A

N78-10559

Unclas
G3/44 50490

JSC-12973

SOLAR POWER SATELLITE

CONCEPT EVALUATION

ACTIVITIES REPORT

JULY 1976 to JUNE 1977

VOLUME I - SUMMARY

VOLUME II - DETAILED REPORT

Lyndon B. Johnson Space Center
Houston, Texas 77058

CONTENTS

Section		Page
I	INTRODUCTION	I-1
II	CONCLUSIONS	II-1
III	PROGRAM REQUIREMENTS	III-1
	A. U.S. Projected Energy Demand	III-1
	B. SPS Implementation Effect on Projected Energy Demand.	III-1
	C. U.S. Siting Considerations	III-5
	D. Electrical Power Demands for the Western Hemisphere and the World	III-5
	E. References	III-6
IV	SATELLITE POWER STATION	IV-1
	A. Satellite Systems Definition	IV-1
	B. Solar Energy Collection System (SECS)	IV-5
	C. Microwave Power Transmission System.	IV-19
	D. Microwave Reception and Conversion System	IV-25
V	SPACE CONSTRUCTION AND MAINTENANCE SYSTEM	V-1
	A. System Definition Study Construction Results	V-1
	B. Orbital Construction Support Equipment Study	V-7
	C. Automated Construction	V-11
VI	SPACE TRANSPORTATION SYSTEMS	VI-1
	A. Systems Requirements and Analysis	VI-1
	B. Heavy-Lift Launch Vehicle	VI-3
	C. Personnel and Priority-Cargo Launch Vehicle . . .	VI-7
	D. Cargo Orbital Transfer Vehicle	VI-9
	E. Personnel Orbital Transfer Vehicle	VI-11
	F. Summary of Projected Transportation System Characteristics	VI-14
VII	ENVIRONMENTAL FACTORS	VII-1
	A. Microwave Transmission and Reception	VII-1
	B. In-Space Operations	VII-3
VIII	MANUFACTURING, NATURAL RESOURCES, TRANSPORTATION, AND ENERGY CONSIDERATIONS	VIII-1
	A. Aluminum Requirements	VIII-1
	B. Gallium Supply	VIII-1

Section Page

C. Surface Transportation Requirements VIII-2
D. System Energy Balance VIII-4

IX PROGRAM DEVELOPMENT IX-1

A. NASA/ERDA SPS Concept Development and Evaluation Program Plan 1977-1980 . . . . IX-1
B. Technology Advancement Plan IX-2
C. Related Activities IX-13

X PROGRAM COST X-1

A. Scope of the Cost Estimating Effort X-1
B. Cost Sensitivities X-1
C. Updated JSC Cost Estimates X-7

XI ALTERNATIVE SYSTEM COMPARISONS XI-1

A. Technological Status XI-2
B. Cost Comparisons XI-4
C. Environmental Considerations XI-6
D. Summary Remarks XI-7

TABLES

Table		Page
IV-1	A SUMMARY OF EVALUATION FACTORS FOR CONSTRUCTION LOCATION	IV-4
IV-2	TECHNOLOGY ADVANCEMENT REQUIREMENTS	IV-11
IV-3	30-YEAR DEGRADATION ESTIMATE REFERENCE CONFIGURATION (SILICON) ENERGY CONVERSION	IV-14
IV-4	NUMBER OF 5-GW RECTENNAS ALLOWABLE ON EACH REGIONAL GRID BECAUSE OF ECLIPSES AT THE EQUINOXES FOR 2025 (NO STORAGE SYSTEM)	IV-26
V-1	CONSTRUCTION CREW SIZE COMPARISON	V-4
VI-1	HLLV CANDIDATE CONFIGURATION CHARACTERISTICS	VI-4
VI-2	WINGED-LAUNCH-VEHICLE PAYLOAD VERSUS LAUNCH SITE CAPABILITY	VI-7
VI-3	HLLV RANGE OF PROJECT D ESTIMATES	VI-16
VI-4	PLV RANGE OF PROJECTED ESTIMATES	VI-16
VI-5	COTV RANGE OF PROJECTED ESTIMATES	VI-17
VI-6	POTV RANGE OF PROJECTED ESTIMATES	VI-17
VI-7	RELATIVE TRANSPORTATION COSTS FOR SPS CONSTRUCTION ONLY, FY 1977	VI-18
VI-8	RELATIVE TRANSPORTATION COSTS FOR SPS CONSTRUCTION, FY 1976	VI-18
VIII-1	FUEL DELIVERY REQUIREMENTS	VIII-3
IX-1	NASA-ERDA PROGRAM DEFINITION PLAN (CONCEPT EVALUATION)	IX-1
IX-2	CRITICAL TECHNOLOGY AREAS	IX-3
IX-3	SCALING FACTORS FOR SCALE MODEL LEO STRUCTURAL TEST OF GSO SPS ($s \sim 15$)	IX-14
X-1	EFFECT OF SCENARIO B ON COST OF POWER	X-6
X-2	COST COMPARISONS	
	(a) Cost of subsystem	X-8
	(b) Cost of power	X-8

Table		Page
X-3	WORK ELEMENTS FOR SOLAR POWER SATELLITE	X-10
X-4	TOTAL COST SUMMARY FOR SPS	X-12
XI-1	ALTERNATIVE POWER SYSTEMS	
	(a) Conventional systems	XI-1
	(b) Advanced systems	XI-1
XI-2	TECHNOLOGY STATUS AND PROJECTIONS	XI-3
XI-3	5000-MW PLANT ENVIRONMENTAL FACTORS	XI-8

FIGURES

Figure		Page
I-1	Projected requirements for U.S. electrical power . . .	I-2
III-1	Projections of U.S. electrical energy requirements and possible SPS implementation.	III-2
III-2	Electrical power projections by several organizations	III-3
III-3	Projected values for power-generation capacity, derived from ERDA (ref. III-6)	III-4
IV-1	Analysis and configuration evolution	IV-5
IV-2	Performance comparison of energy conversion candidates	IV-6
IV-3	Performance degradation comparison	IV-7
IV-4	Satellite size comparison	IV-8
IV-5	Satellite total mass comparison (with no margin)	IV-9
IV-6	Relative constructability ratings	IV-10
IV-7	Hughes Research Laboratories GaAlAs/GaAs solar cell efficiency	IV-14
IV-8	Isogrid test article	IV-17
IV-9	Isogrid cylinder fabricator	IV-18
IV-10	Transmit array diameter (km)	IV-21
IV-11	Transmit array diameter (km)	IV-22
IV-12	Collection efficiency for a one-solid and a three-segmented antenna	IV-23
IV-13	MPTS antenna - tetratruss model	IV-24
V-1	Construction machine and crew size comparison	V-3
V-2	Satellite construction facility comparison	V-5
V-3	Preliminary relative constructability rating	V-6
V-4	Concept for docking/berthing large modules	V-7

Figure | Page

V-5	SPS baseline configurations	V-8
V-6	OCSE inventory tree	V-9
V-7	OCSE candidate concepts	V-12
V-8	Beam builder concept	V-13
VI-1	Modified single-stage to orbit (SSTO)	VI-5
VI-2	Two-stage ballistic HLLV (Boeing)	VI-6
VI-3	Two-stage winged HLLV (JSC)	VI-8
VI-4	Personnel launch vehicle (PLV)	VI-10
VI-5	Cargo orbital transfer vehicle ($COTV_G$) characteristics	VI-12
VI-6	Crew module concept	VI-13
VI-7	Crew rotation passenger module	VI-14
VI-8	Personnel orbital transfer vehicle (POTV) characteristics	VI-15
VIII-1	Payback time in years versus SPS mass chemical transplant	VIII-4
IX-1	Space fabrication experiment	IX-7
IX-2	Space fabrication experiment	IX-9
IX-3	Microwave energy transmission project	IX-11
IX-4	Space transportation	IX-16
IX-5	Space transportation	IX-17
X-1	Major SPS cost drivers	X-2
X-2	Effect of solar cell efficiency on power cost	X-3
X-3	SPS cash flow	X-4
X-4	Effect of return on investment on power cost	X-5
X-5	Effect of DDT&E amortization on cost of electricity	X-7
X-6	Summary of estimates	X-13

Figure | Page

XI-1	Power-generation costs, showing various presently used and potential systems in relation to present and projected costs	XI-5
XI-2	Cost of electricity versus fuel cost showing SPS costs relative to nuclear, coal, and oil-fired systems	XI-7

I. INTRODUCTION

Increasing requirements for energy in the United States and the world continue to deplete the fossil fuels at an increasing rate. Projections for the U.S. requirements for electrical energy show a significant increase in generating capacity even if conservation policies are successful (fig. I-1).

The conscious efforts by consuming nations to initiate energy conservation policies may slow the rate of increase in consumption, but these efforts cannot provide a permanent solution. The energy plan proposed in April 1977 by President Carter emphasized conservation and heavier dependence on coal. For long-term solutions, emphasis must be placed on renewable or nondepletable energy sources such as solar, geothermal, ocean thermal, and nuclear fusion.

The most promising candidate for a nondepletable energy source appears to be solar power because of its technical feasibility, environmental attractiveness, and availability. Two types of solar power systems to be considered are ground-based and solar power satellites (SPS). The use of space-based solar power has the advantage of not being subject to reduced solar radiation (insolation) by the atmosphere, clouds, haze, and nighttime, providing power 24 hours a day on a near-continuous basis.

The Lyndon B. Johnson Space Center (JSC) report entitled "Initial Technical, Environmental, and Economic Evaluation of Space Solar Power Concepts" (JSC-11568) released in 1976 established the technical feasibility of an SPS program to provide a significant portion of the future electrical demand, beginning as early as 1995. The initial summary results were reported as follows.

A. Technical feasibility - An engineering project of major proportions but not requiring scientific breakthroughs

B. Technical data - range of estimates

1. Energy conversion - Transmission efficiencies, percent . . 8 to 4
2. 10 000-MW plant - Size, km^2 . . . . 90 to 180
   Weight, tons . . . . 50 000 to 100 000
3. Estimated cost of electricity, mills/kWh . . . . 29 to 115

C. Major cost drivers - solar cell performance and space transportation

D. Significant environmental benefits but questions need to be answered

E. Energy payback ratio promising ≈1 year

F. Natural resource requirements reasonable

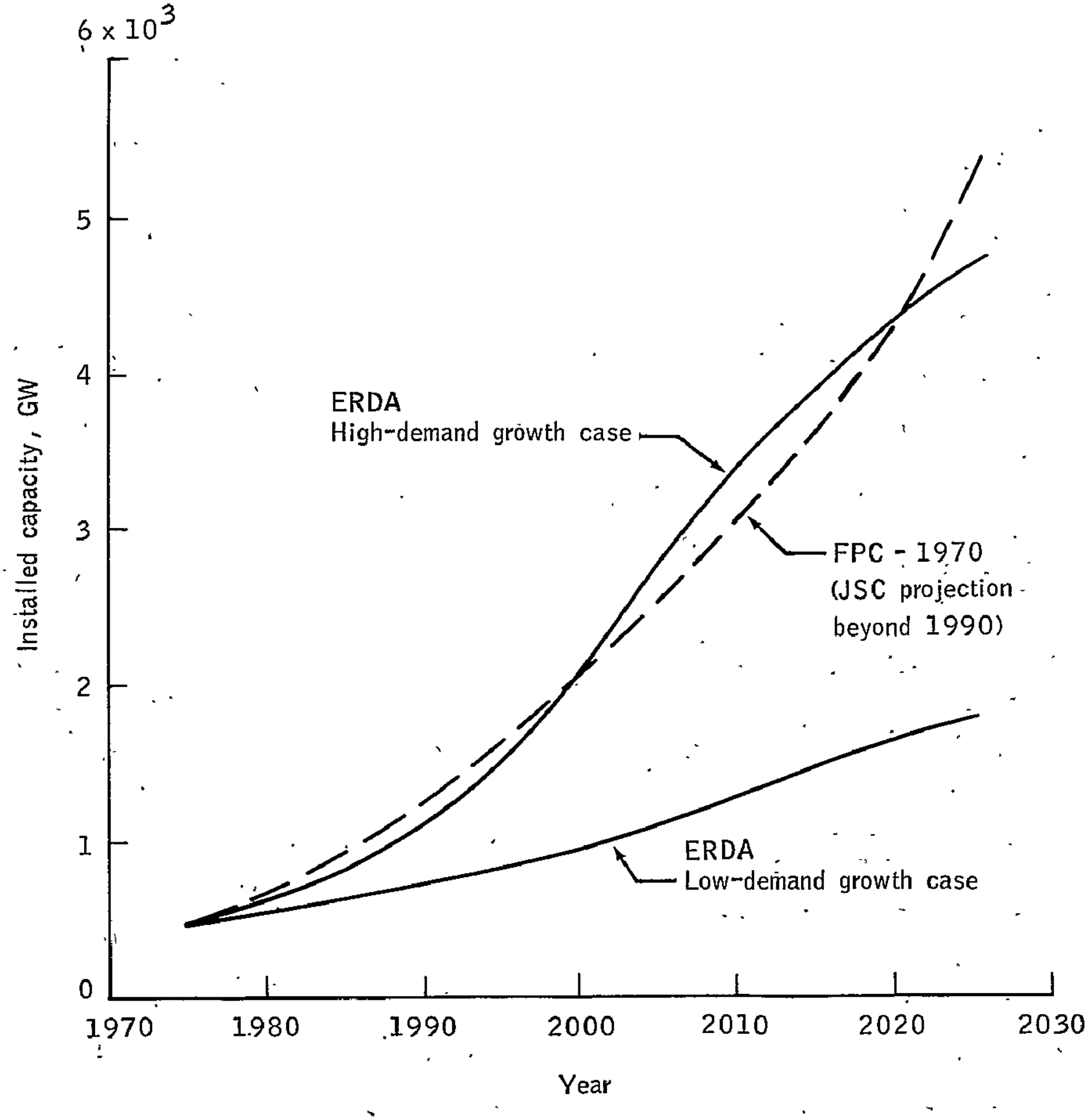


Figure I-1.- Projected requirements for U.S. electrical power.

G. Existing technological and industrial base

H. "Competitive" with other advanced systems

The JSC Systems Definition effort from July 1976 to June 1977 is the subject of this report, and presents comparative data of various designs of thermal engine and photovoltaic SPS concepts. The major area of the SPS system examined during this study period includes solar cells, transportation, rectenna structure, and environmental issues.

This document (vol. I) presents a summary of the results of the 1977 studies. Volume II contains the detailed individual studies on which this summary was based.

II. CONCLUSIONS

The satellite power concept continues to appear technically feasible and economically viable after more detailed evaluation and systems definition. This systems definition effort provided a more thorough understanding of the system design options and performance criteria. Conclusions derived from this year's effort, both in-house and contracted, are summarized as follows.

Candidate baseline concepts have presently been narrowed to a photovoltaic silicon system with annealing and a thermal engine system using the Brayton cycle, primarily because of a combination of their performance and relatively low development risk. Potential performance and cost gains associated with the photovoltaic gallium arsenide and the thermal Rankine systems warrant their continued evaluation as advanced technology options.

The steam Rankine and thermionic conversion systems are so heavy that they should be dropped from consideration at this time.

Recent studies show that a photovoltaic silicon system with no solar concentration is smaller, lighter, and costs less than a silicon system with a concentrator area ratio of 2. Analysis indicates that the area ratio of 2 actually yields an effective concentration ratio (CR) of 1.40 at the beginning-of-life (BOL) and only 1.31 after 30 years because of degradation of solar cells and concentrators.

Initial test results indicate that radiation-damaged solar cells can be restored to near-original performance with thermal annealing using directed-energy techniques which do not significantly heat the cell substrate.

The microwave power transmission system (MPTS) operating at 2450 MHz can be sized down from the proposed 5 GW for each rectenna to as low as 1 GW with a loss in overall MPTS efficiency of about 3 percent; however, preliminary estimates indicate a higher cost of power.

SPS concepts in which the MPTS is divided into a number of station-kept elements result in significantly lower overall microwave link efficiencies because of high sidelobes and grating lobes. As an example, an MPTS with only three separate antenna elements results in a collection efficiency of 60 percent as compared to 88 percent for a system with a single transmitting antenna of equal total area.

The requirements for very low coefficient of thermal expansion and high modulus of elasticity for the SPS structure dictate that the structural material for both the solar collector and transmitting antenna should be a composite of plastic resin and reinforcing fibers.

SPS construction in either low Earth orbit (LEO) or geosynchronuous equatorial orbit (GEO) remains viable; however, further analysis indicates

LEO construction could be as much as 25 percent lower in overall transportation cost through the use of a GEO transfer mode in which a high-I_{sp} electric propulsion system is provided power from part of the operational electric generating capability of the SPS. More detailed analysis of evaluation factors is required before a clear construction orbit choice can be made.

LEO tests of scale models for the full-scale GEO SPS structure require a configuration in which the full-scale linear dimensions are reduced by a factor of 15.

Operating costs of winged and ballistic heavy-lift launch vehicles (HLLV) are comparable, although the development and facility costs of the winged vehicles are somewhat higher.

SPS transportation system propellant requirements can be met economically by coal gasification and the pipeline transportation of GH_2 rather than by conventional production of GH_2 from natural gas.

The use of a returnable payload shroud or compartments reduces HLLV costs by as much as $7 million per flight. Such returnable payload compartments seem compatible with the densities of anticipated SPS payloads.

Analyses indicate that expected launch costs of approximately $9 per pound to LEO at SPS launch rates may be achieved, compared to $15 per pound defined in last year's report.

Cost-optimum trip times approach 1 year for "self-powered" electric propulsion from LEO to GEO. Flight control at low altitudes requires additional thrust, however, to counter gravity gradient torques. Application of these higher thrust levels result in trip times of approximately 200 days.

Studies conclude that a scaled-up ion engine using argon is feasible and provides an attractive alternative to the MPD engine.

A two-stage completely reusable chemical cargo orbital transfer vehicle (COTV) is less expensive to operate than the 2-1/2-stage vehicle with an expendable tank assumed last year for the GEO construction case.

Remote areas in the western United States appear capable of supporting the two-staged winged launch vehicle at SPS operational launch rates, utilizing special railways for the return of vehicles to the launch site.

Energy payback for each SPS ranges between 0.9 and 1.6 years utilizing an all aluminum supporting structure for the rectennas. Utilizing steel for the support structure would reduce the energy payback by 0.1 year.

Availability of gallium is uncertain. Current supplies are obtained from aluminum production and coal fly ash is a candidate source. Obtaining gallium from seawater does not appear economically feasible.

Surface transportation requirements may be easily met with the exception of fuel delivery to the launch site. Meeting this fuel delivery requirement may require a special pipeline, or production of hydrogen and oxygen at the launch site.

Weather modification due to rectenna waste heat is negligible.

The additive microwave power densities in distant sidelobes for multiple satellites have been determined to be less than 10^{-6} watts/cm^2, some four orders of magnitude below the limits for human tissue heating effects.

The precipitation of high-energy particles in space appears to offer potential means of reducing radiation protection requirements during LEO construction and LEO to GEO transfer. Further study is being done to analyze the feasibility of this concept.

Based on current conditions, a large space structure the size of an SPS in LEO could receive an estimated 10 to 100 impacts per year as compared to only 1 to 10 in GEO in a 30-year period. By the year 2000, the number of predicted impacts for a given area could increase significantly as a result of collisions between objects already in orbit; however, further analysis is required to identify (1) the number of small objects in orbit between 0.1 cm and 10 cm and (2) the effects of collisions between orbiting objects (i.e., number and size of debris products).

Detailed comparisons of 13 alternative power sources indicate that the SPS concept offers the significant environmental advantages of very low air pollution, no major cooling water requirements, and no residual material for storage and/or disposal. The SPS is cost competitive with the conventional fuel-consuming systems (i.e., oil, gas, coal, and nuclear) in the low range of projected cost of 30 to 50 mills/kWh (1976 dollars). In the upper range of projected costs (50 to 115 mills/kWh), the SPS is competitive with advanced concepts such as ground solar, ocean thermal, and nuclear fusion.

Rectenna cost analysis shows that overall SPS costs are very sensitive to individual cost estimates for rectenna support structure, dipoles, and diodes.

III. PROGRAM REQUIREMENTS

A. U.S. Projected Energy Demand

The previous JSC SPS study included a projection of the nation's electrical energy requirements through the year 2025. This projection is shown in figure III-1. Many other organizations have made projections of electrical energy consumption, as indicated in figure III-2. For reference, the previously used Federal Power Commission (FPC) projection is shown in figure III-2 along with projections by the Department of Interior, Electrical World magazine, Shell Oil Company, the Electric Power Research Institute, and the Energy Research and Development Administration (ERDA) (references III-1 to III-5).

The FPC projection is a pre-1973 oil-embargo projection that assumed a continuation of the historical growth rate of about 6 percent. As a result, it is somewhat higher than the other projections, which include the effects of various levels of conservation. In a recent ERDA projection (fig. III-3) of installed capacity requirements, the high-demand growth case is similar to the corresponding capacity requirements of the FPC energy demand projection. The assumptions for the ERDA projections are as follows.

1. 7 percent growth rate to 1985
2. 6.4 percent growth rate from 1985 to 2000
3. 3.3 percent growth rate from 2000 to 2025
4. Continuing shift by users from other forms of energy to electricity

The low-demand growth case is based on the following assumptions.

1. 3.7 percent growth to 2000
2. 2.4 percent growth from 2000 to 2025
3. Significant conservation efforts, and no increased degree of electrification

As indicated in figure III-3, capacity requirements projected to the year 2025 differ by more than a factor of 2, depending on the growth rate assumed.

B. SPS Implementation Effect on Projected Energy Demand

In the initial JSC SPS study, the SPS implementation rates (fig. III-1) were assumed for study purposes. The three scenarios developed resulted in providing the following percentage of electrical energy requirements in the year 2025.

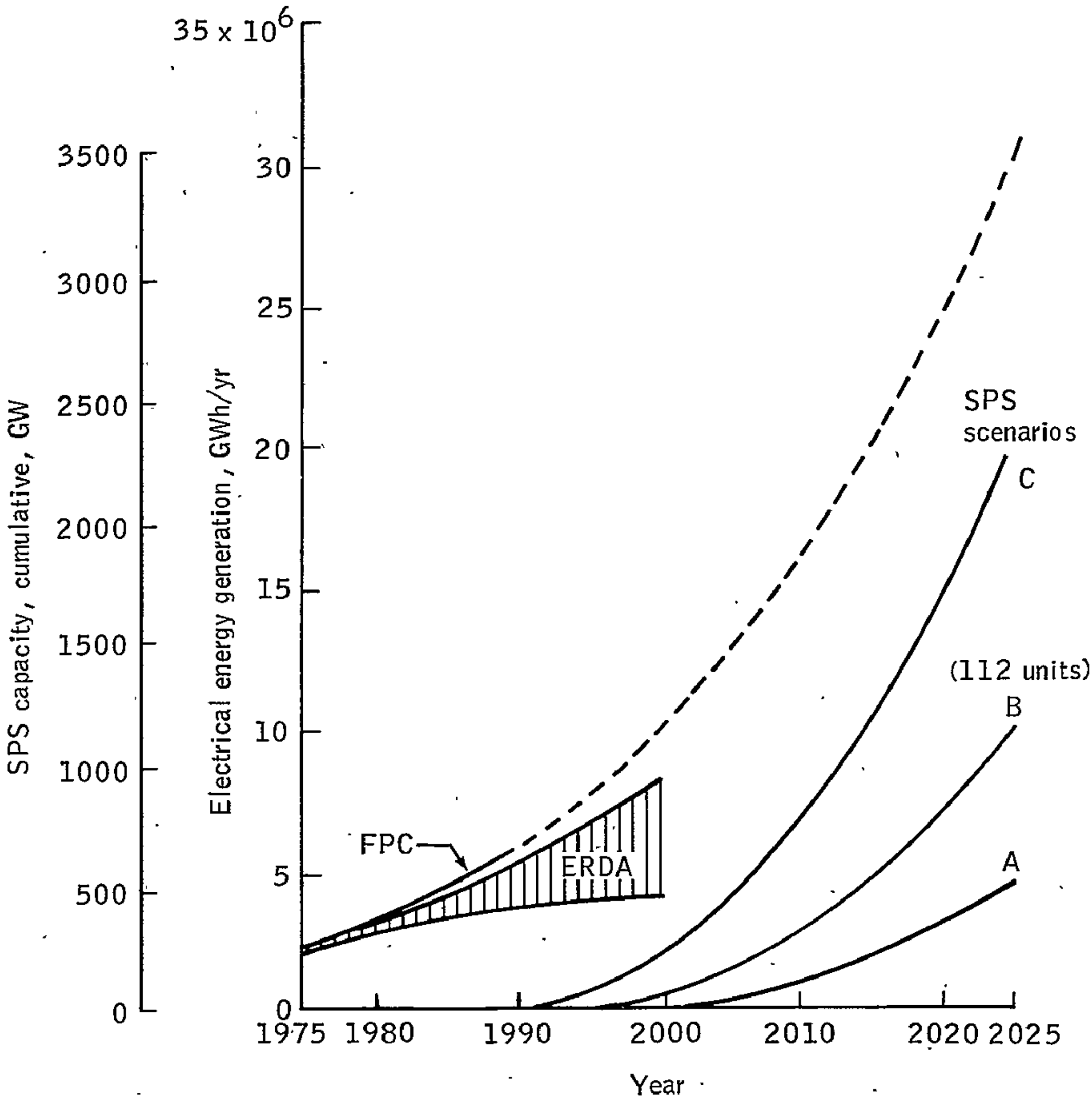


Figure III-1.- Projections of U.S. electrical energy requirements and possible SPS implementation.

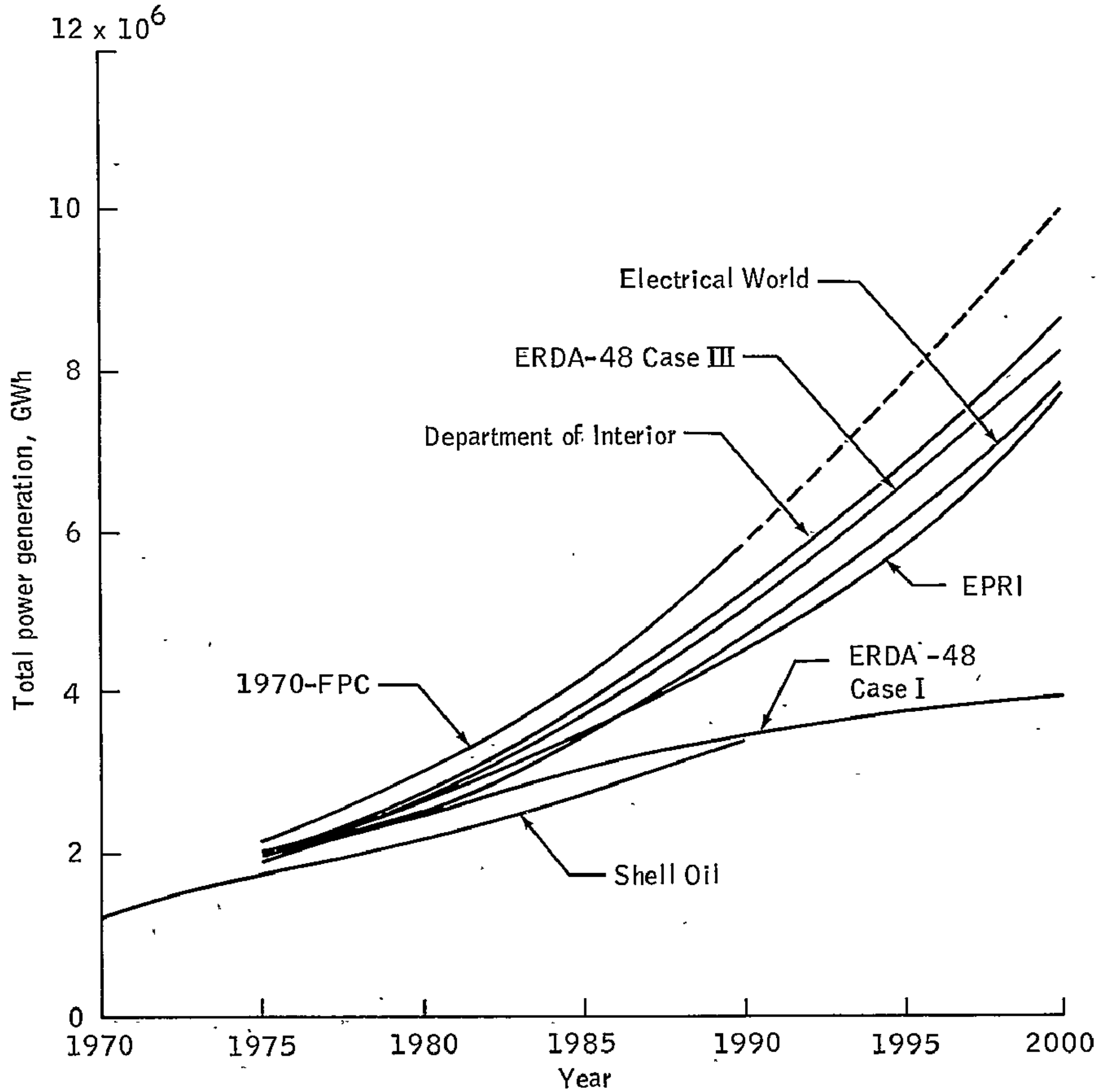


Figure III-2.- Electrical power projections by several organizations.

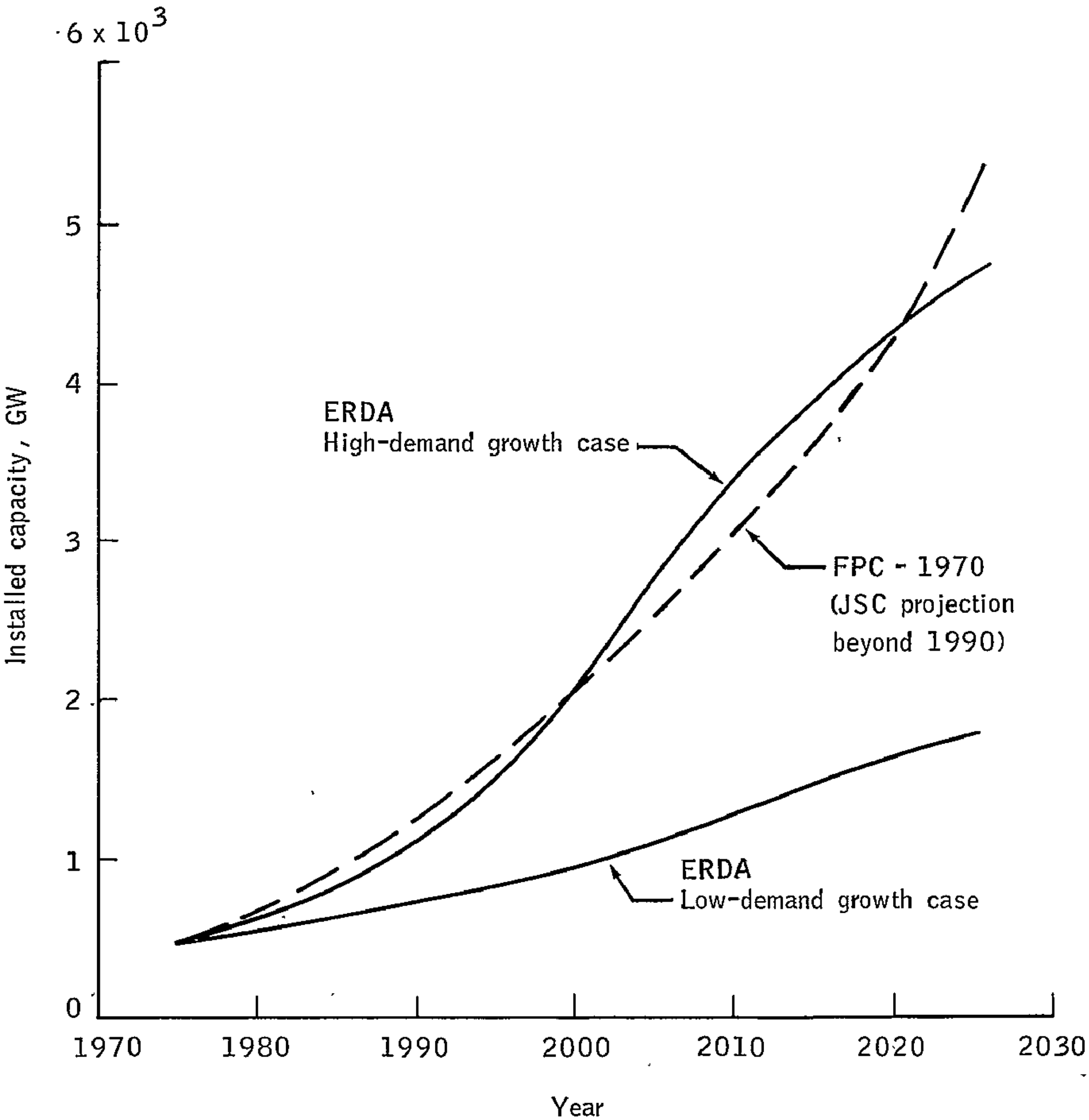


Figure III-3.- Projected values for power-generation capacity, derived from unpublished ERDA data (ref. III-6).

Scenario A - 16 percent

Scenario B - 34 percent

Scenario C - 62 percent

Scenario B was used as an example to determine program requirements and to perform economic analyses. Sized at 10 GW per SPS, a total of 112 satellites would be required in 2025. It should be emphasized that this relatively large number was used to reveal potential environmental, natural resources, and economic problems. Several substudies reported herein have continued to use the scenario B implementation rate to flush out potential limitations of the SPS concept.

Use of the low-demand growth case shown in figure III-3 results in the need for fewer SPS units to achieve the same percentage of 2025 electrical energy needs. For example, 36 SPS units (instead of 112) in operation in 2025 would produce 34 percent of the low demand growth electrical energy needs. An average implementation rate of slightly over one SPS per year for 30 years would yield the 36 units.

C. U.S. Siting Considerations

The choice of rectenna site location is studied in the program requirements because the latitude of the site determines rectenna size (cost). The location is also significant with respect to land cost and availability, power-transmission requirements, and environmental considerations.

The principal objective of the rectenna siting analysis is to assure that the rectenna power system is located near the demand area to minimize costs of electricity to the consumer. Present trends in social and economic values indicate that 85 percent of the U.S. population will live in metropolitan areas in the year 2000. It has been shown that electrical consumption for a given region usually reflects the population density of that region. In the year 2000, it is predicted that 41 percent of the population will live in the metropolitan belt stretching along the Atlantic seaboard west to Chicago, and another 13 percent will live in a region lying between San Francisco and San Diego along the California coast. Although specific sites should be determined from geographical and economic considerations, these two regions should be considered for analysis of rectenna systems locations.

D. Electrical Power Demands for the Western Hemisphere and the World

Electrical energy produced by SPS is potentially an exportable commodity; therefore, the electrical energy needs of countries other than the United States could have an effect upon SPS program requirements.

An analysis was conducted using population, gross national product, and electrical energy consumption statistical data to project the effect of rapidly increasing populations and the demand for energy resources into the SPS operational period. For study purposes, Mexico and Brazil were selected as the major developing countries most likely to influence

hemispheric trends. The United States and Canada were selected as the major developed countries in this hemisphere for the study.

The projections of this study show that the populations of the developing countries will continue to grow rapidly into the next century, while the populations of the developed countries will stabilize. Because of continuing increases in per capita gross national product for all the countries studied, the projection of increased electrical energy requirements is dramatic. As an example, conservative projections show that Brazil's population will double between 1970 and 2000 and will reach the U.S. level by the year 2035. Provided that energy is available, Brazil's annual electrical energy consumption level will reach about 2 x 10^{12} kWh in 2013, the level of U.S. consumption in 1975. Brazil currently imports over half of its primary energy. This example illustrates the plight of most underdeveloped and developing countries, worldwide. It is evident that strong competition will exist for the available energy with a large market for the energy exporters.

E. References

III-1. Initial Technical, Environmental and Economic Evaluation of Space Power Concepts. JSC-11568, 1976.

III-2. United States Energy Through the Year 2000. Bureau of Mines, U.S. Dept. of the Interior, 1975.

III-3. Electrical World magazine, pp. 58-62, December 15, 1976.

III-4. The National Energy Outlook 1980-1990. Shell Oil Company, 1976.

III-5. Role of Fossil Fuels for Electricity Production. Electric Power Research Institute, 1977 (Draft).

III-6. Comparing New Technologies for the Electric Utilities. ERDA 76-141, 1976 (Draft revision A).

IV. SATELLITE POWER STATION

This section presents the results of the in-house and contracted efforts which together make up the SPS system definition and concept evaluation study for the power station (including the rectenna).

The results included in this section are primarily summaries of individual studies related to specific areas of special interest rather than an "across-the-board" analysis of the total satellite system as was last year's system definition study.

A. Satellite Systems Definition

Part of the SPS system definition work in this period was done in the first part of a two-part study contracted to Boeing ("SPS System Definition Study," NAS 9-15196). Part I of the study began November 22, 1976, and ended May 1, 1977, and had as its objectives the development of comparative data to aid NASA in the evaluation of two basic questions which remained after the 1975-76 JSC study report (JSC-11568). These two major questions were: (1) What is the overall most effective means of accomplishing solar energy to electrical energy conversion on an SPS in geosynchronous orbit and (2) at what location (or locations) in space should the various phases of SPS construction and assembly be done?

As a point of departure, two reference configurations were established at the beginning of the study. These were the JSC planar truss photovoltaic system described in the August 31, 1976, JSC study report (JSC-11568), and the Boeing Brayton thermal engine system developed in a 1976 study for MSFC (NAS 8-31628).

1. Energy Conversion Question

A range of energy conversion candidates was considered that included the following.

a. Photovoltaic

(1) Single crystal

(a) Silicon

(b) Gallium arsenide

(2) Advanced thin film

(a) Silicon

(b) Gallium arsenide

(c) Cadmium sulfide

(d) Copper indium selenide

b. Thermal cycle

   (1) Brayton

   (2) Modified Brayton

   (3) Rankine

   (4) Thermionic

A comparative evaluation was made of these candidates using a set of evaluation factors designed for relative assessment of each candidate. These evaluation factors or "comparators" are as follows.

a. SPS performance

b. Performance degradation

c. SPS size

d. SPS mass

e. System complexity

f. System maintainability

g. Construction requirements

h. Transportation requirements

i. Technology advancement requirements

j. System cost differential factors

k. Environmental effects differential factors

l. Materials differential factors

The results of the energy conversion evaluation can be summarized as follows.

a. There are at least four viable energy conversion candidates - photovoltaic silicon, photovoltaic gallium arsenide, thermal Brayton cycle, and thermal Rankine cycle.

b. Thermal engines are more complex, but may require less technology advancement. Radiators require extensive development.

c. Photovoltaics are simple in concept, but a continuous production process for solar cells must be developed to make the concept economically viable.

d. No large differences in DDT&E or production cost projections for energy conversion in the silicon and Brayton candidates have been identified.

Part II of the Boeing study will produce a complete SPS system definition with each element of the system defined to the same level. A goal of the study is to reduce the range of uncertainty in the weight and cost estimates to one-half the range developed in the 1976-77 JSC study. To do this, the number of energy conversion candidates must be reduced to those that show the promise of being most effective, considering all factors; then the more detailed system definition can be done with those selected concepts.

Boeing's recommendations concerning energy conversion for the purposes of Part II of this study are as follows.

a. As a Part II study reference or "baseline," proceed with both the photovoltaic silicon system (with concentration ratio of 1 and annealable) and a thermal engine system using the Brayton cycle. (The Rankine cycle may, in time, supplant the Brayton cycle if recent significantly reduced weight estimates for Rankine turbine compressors for use in space can be substantiated.)

b. The photovoltaic gallium arsenide system concept should be carried in Part II of the study as an advanced technology option.

c. The potential for a large mass reduction in the thermal engine system using the potassium-Rankine cycle should be further evaluated.

d. Thin-film photovoltaic systems should be discontinued in this study until a better data base is available.

e. The steam Rankine system and the thermionic system should be dropped because of their relatively high masses.

The detailed results and supporting analyses of the energy conversion evaluation may be found in the Boeing final report of Part I (published in June 1977) and in section IV.B of this report.

2. Construction Location Question

In the consideration of where the construction of an operational SPS should be accomplished, the primary choices are LEO below the Earth's radiation belt, GEO, or some combination of the two. The most apparent difference between the two locations is that LEO construction allows a low-thrust transfer from LEO to the operational GEO location using a high-I_{sp} electric propulsion system installed on the SPS and powered by part of the operational electric generating capability of the SPS itself.

Several factors favor GEO construction. Atmospheric drag effects are negligible and gravity gradient forces are much less severe. Construction

can take place in near-continuous sunlight. The SPS design does not have to accommodate transfer loads or the installation of the transfer propulsion system. The risk of collision with other orbiting objects during construction and transfer is nearly eliminated. Although orbital transfer with chemical systems is less efficient, they are well known and much quicker than electric systems.

On the other hand, LEO construction has the potential of considerably reducing the launch rate and overall transportation requirements, and could be about 25 percent lower in overall transportation costs.

A summary of the evaluation factors for the construction location question and the associated relative merits of the two alternatives are shown in table IV-1.

The results of the construction location evaluation are that either LEO or GEO construction is a viable option; there is no clear choice at this time. It is possible that both modes would be used, depending upon requirements other than technical. Boeing's recommendation for Part II of the study is to defer the decision until program requirements are more

TABLE IV-1.- A SUMMARY OF EVALUATION FACTORS FOR CONSTRUCTION LOCATION

Evaluation factor	Preferred construction location		Decision driver
	LEO	GEO	
Transportation requirements	•		LEO requires less flights and less on-orbit propellant transfer
Construction requirements	No selection		LEO drag and dark periods vs. GEO radiation and distance
SPS overall design requirements		•	LEO requires modularization and other specialization
SPS performance and degradation potential		•	Degradation due to Van Allen radiation can be compensated
Launch site differential effects	•		Fewer launches for LEO
System startup requirements		•	LEO startup more complex
Operations considerations		•	LEO has more distinct kinds of operations
Collision considerations		•	About 15 collisions/SPS for LEO vs. two for GEO
System cost differential factors	•		LEO about 25 percent cheaper overall transportation
Orbital transfer complexity factors		•	Electric propulsion (LEO) more complex

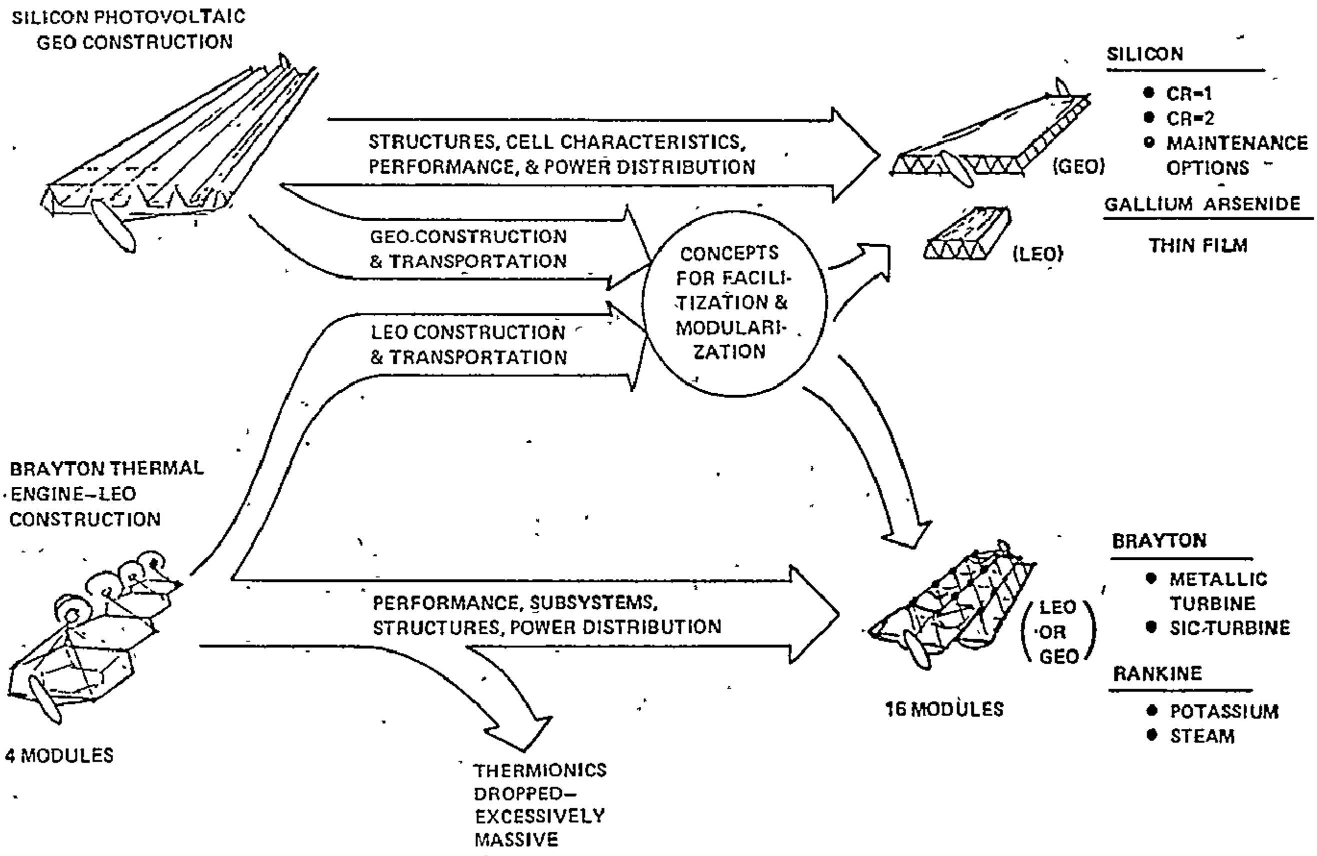


Figure IV-1.- Analysis and configuration evolution.

clearly defined. For the construction facility analysis, the recommendation is to use a modular SPS construction concept which would be required for LEO construction and is a viable approach for GEO construction also.

The detailed results and supporting analyses of the construction location evaluation may be found in the Boeing final report of Part I, published in June 1977.

B. Solar Energy Collection System (SECS)

1. Energy Conversion

a. Energy Conversion System Comparison - Much of the past year's work in evaluating the relative merits of the candidate energy conversion concepts was done in Part I of the SPS System Definition Study contracted to Boeing (NAS 9-15196). This study began by taking as points of departure the truss configuration with single-crystal silicon solar cells (CR=2) developed in the 1976 JSC study (JSC-11568), and the Brayton thermal cycle system developed by Boeing in a study for MSFC (NAS 8-31628). These reference systems were used in comparative analyses of transportation and construction alternatives. The evolution of these analyses and the resulting concepts are shown in figure IV-1.

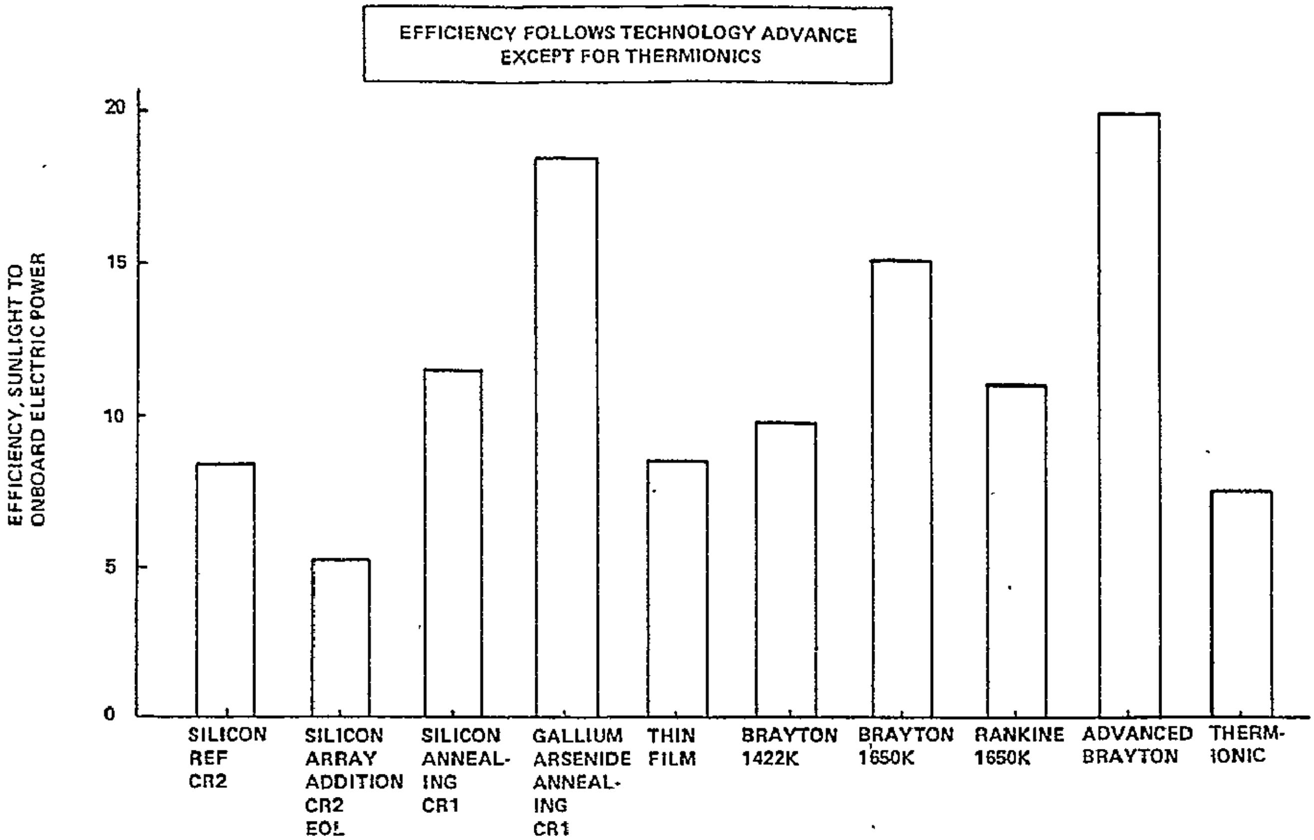


Figure IV-2.- Performance comparison of energy conversion candidates.

A comparative evaluation was made of the energy conversion candidates (listed at the beginning of this section) by using the set of evaluation factors derived for relative assessment of each candidate. A summary of the results of each evaluation factor is given in the following.

SPS Performance - Initially it was believed that the thermal engine systems were much more efficient overall than the photovoltaics; however, the difference is not nearly as large as first thought. Efficiency of a system generally follows technology advancement, and the systems with more development tend to show up as more efficient. As it turns out, in the overall system performance evaluation, efficiency is not a major discriminator unless it is very low. Efficiency comparisons are shown in figure IV-2.

Performance Degradation - Every candidate system is subject to radiation degradation, but to varying degrees. The thermal-engine systems suffer the least, followed by the gallium arsenide systems and then the silicon photovoltaic systems. The left side of figure IV-3 shows how the output of these candidate systems degrades with time. The right side presents the degradation normalized to show what percentage of total satellite mass is affected by the degradation. For example, the thermal systems degrade because of the gradual loss of reflectivity in the thin

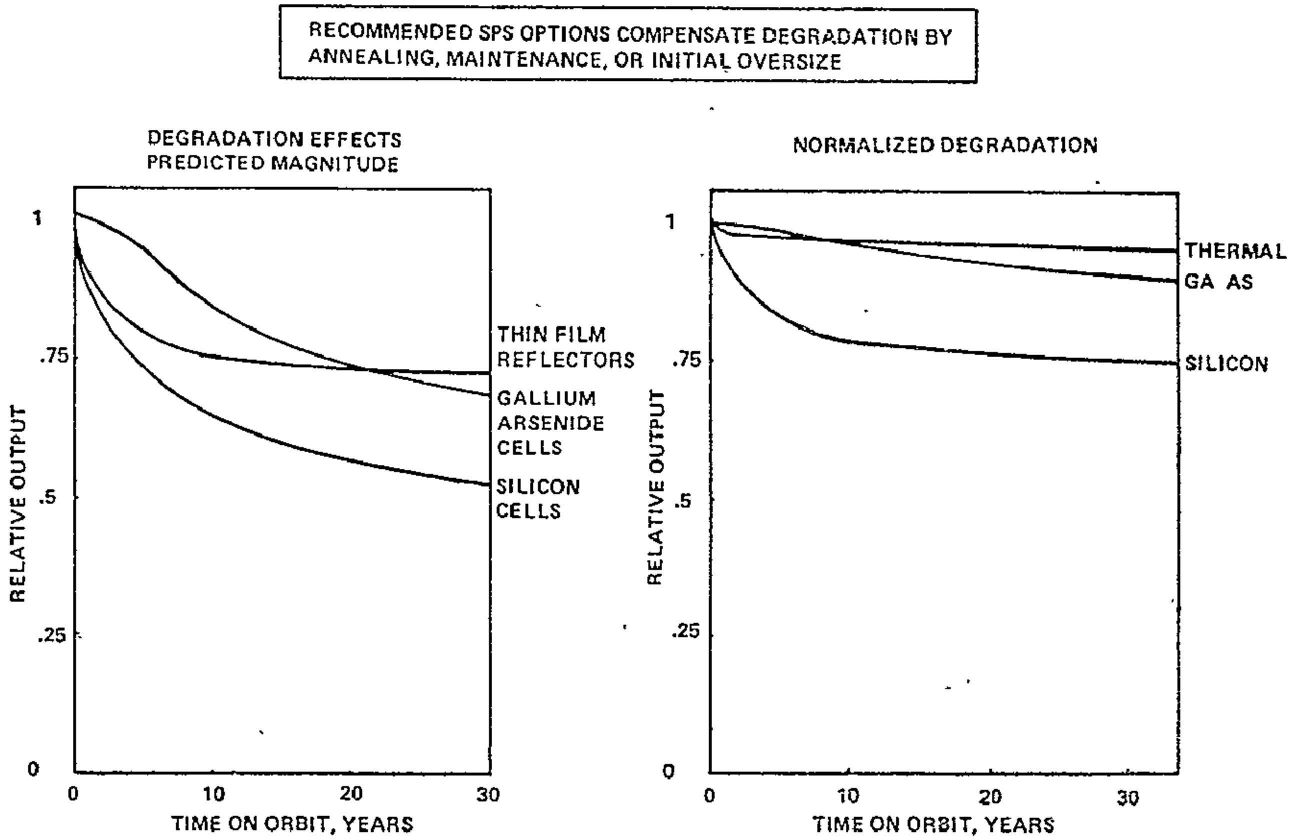


Figure IV-3.- Performance degradation comparison.

film concentrators which account for only a small part of the total satellite mass. For all the recommended concepts, degradation was compensated for in the system comparisons by initially oversizing, periodic adding on more energy collectors, by annealing, or some other maintenance. This compensation can be represented by size, mass, and cost which makes radiation degradation relatively unimportant as an <u>INDEPENDENT</u> evaluation factor.

Satellite Size - Figure IV-4 shows that an annealable gallium arsenide system has the smallest area with the Brayton system ranking second. Silicon systems with no concentration (CR=1) are considerably smaller than those which have a concentration ratio of 2 (CR=2). The estimate for thin film photovoltaics is much more uncertain than the others because less data are available for these systems today. Total platform area does not seem to be as strong a discriminator as some others, where area should be understood as distinct from parameters such as mass that are natural concomitants of size.

Satellite Mass - Figure IV-5 shows a relative mass comparison with NO margin included in the totals. The reference silicon (CR=2) system was sized for a beginning-of-life (BOL) output of 10 GW total and, for reference, carried no penalty for maintaining a relatively constant output.

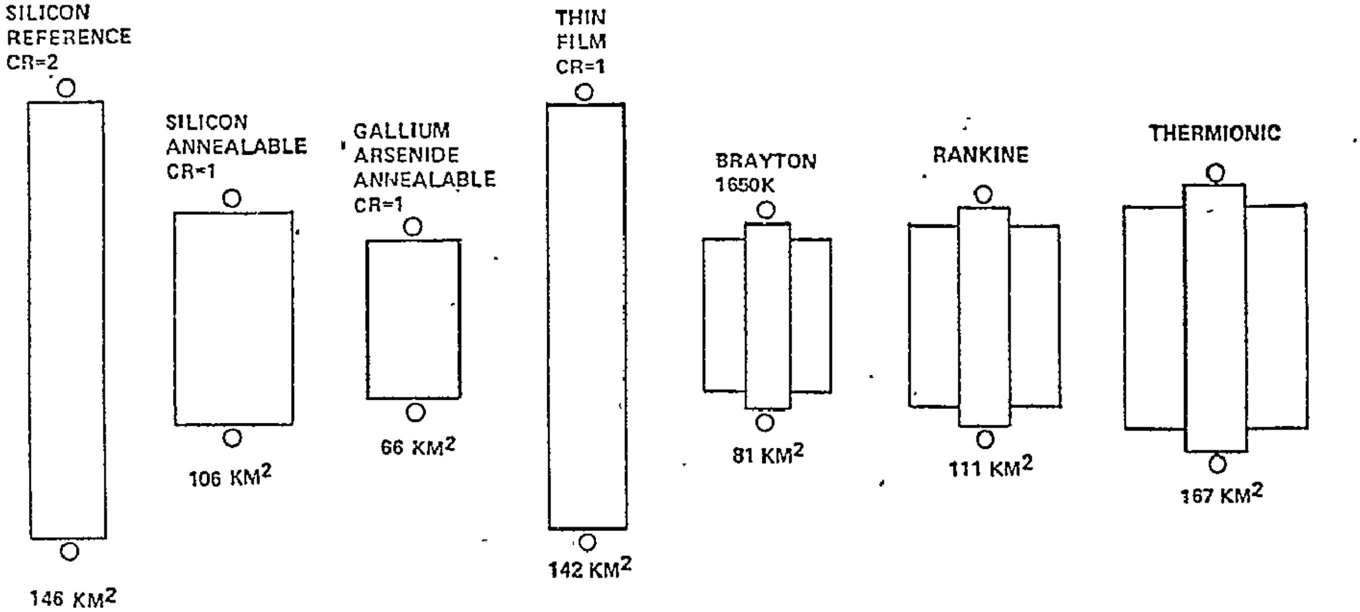


Figure IV-4.- Satellite size comparison.

This comparison clearly shows the tremendous potential advantage in having the capability to anneal radiation damage to restore initial conditions as opposed to periodically adding new energy collectors to maintain BOL power output. Initial tests were made of an annealing concept which uses an electron beam to heat the outer, damaged part of the solar cell momentarily with a directed energy pulse without any significant heat diffusing into the substrate. Initial estimates indicate that about six remotely operated annealing machines, each approximately 2 m square by 3 m long, could keep the performance of a silicon photovoltaic system near 100 percent by continually traveling the surface of the solar array.

The lightest concept was the gallium arsenide system. Because both the steam-Rankine and thermionic systems were so heavy, it is recommended that they be dropped from further consideration at this time.

System Complexity - Complexity is difficult to quantify. For instance, the thermal systems have about five times as many UNIQUE parts or subassemblies as the photovoltaic systems. However, the photovoltaics are made up of 1000 times as many TOTAL pieces. Since integration complexity of systems is usually a function of the number of UNIQUE parts, the thermal systems are considered more complex than the photovoltaic systems.

Maintainability Factors - Both photovoltaic and thermal energy conversion systems have maintenance problems, but conceptual solutions to both have been found. Roughly 5 to 10 manhours per hour for annealing are needed with the photovoltaic system and slightly more than 10 manhours per hour with the thermal system for mechanical repair and replacement. It is conceivable that those manhours might be spent on the ground if suitable

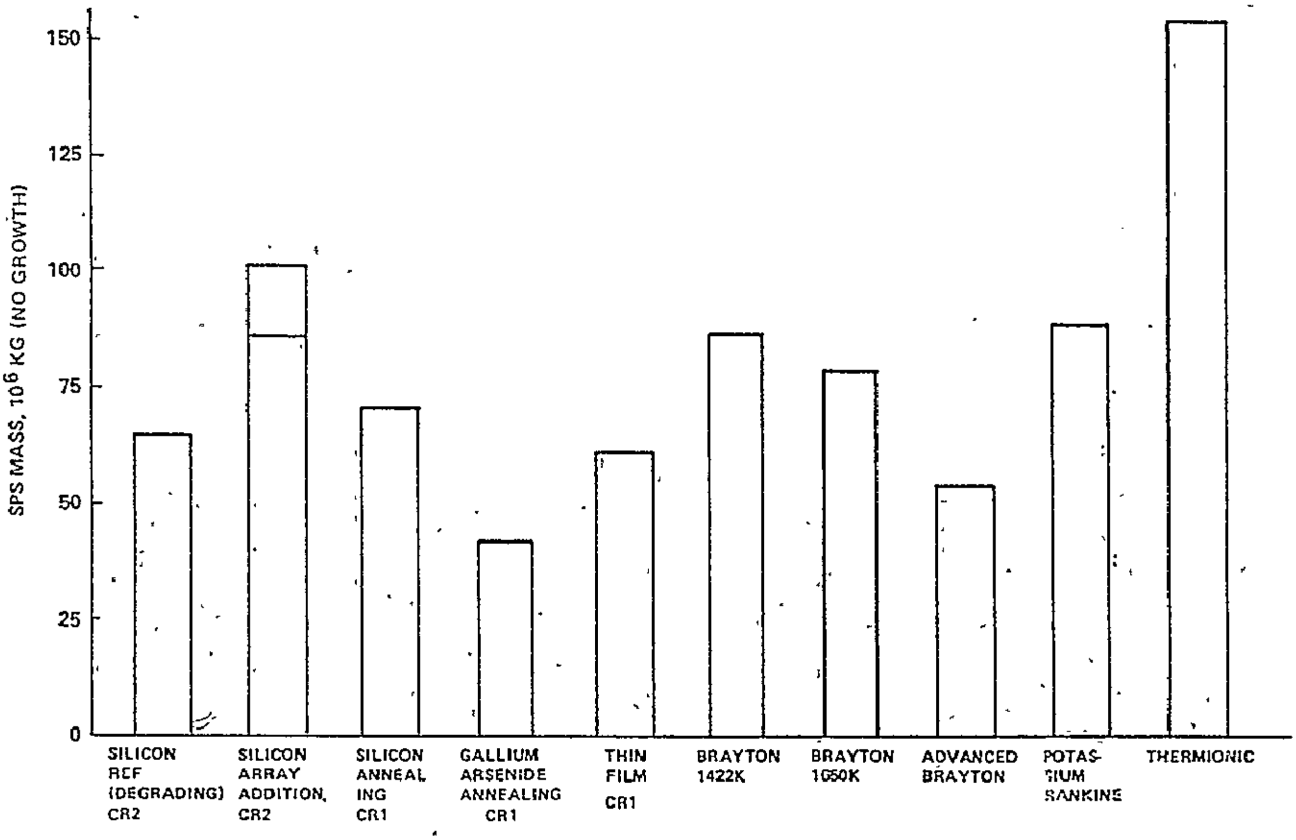


Figure IV-5.- Satellite total mass comparison (with no margin).

automated, remotely controlled systems can be developed. It is likely that these maintenance requirements will be overshadowed by that for the microwave transmitter.

Construction Requirements - Figure IV-6 illustrates relative constructability of candidate concepts at LEO and GEO, and is based on a number developed in the construction analysis. The length of the bars is a weighted relative measure of constructability with a longer bar indicating a better rating. The photovoltaic systems are easier to construct because they are less mechanically complex. Here can be seen one of the reasons for the desirability of no-concentration photovoltaic systems over those with concentration. The construction process is considerably less complex.

Transportation Requirements - Although there was no great difference in total launch mass between the best photovoltaic and thermal systems, the photovoltaics have a significant advantage in packaging density. Photovoltaic systems components and materials can be packaged for launch to a density about 20 times that of the thermal systems. Some thermal engine components will barely fit into the reference launch vehicle payload dimensions. The average achievable packaging density was approximately 1300 kg/m^2 (81 lb/ft^3) for the photovoltaics and approximately 72 kg/m^2 (4.5 lb/ft^3) for the thermal systems.

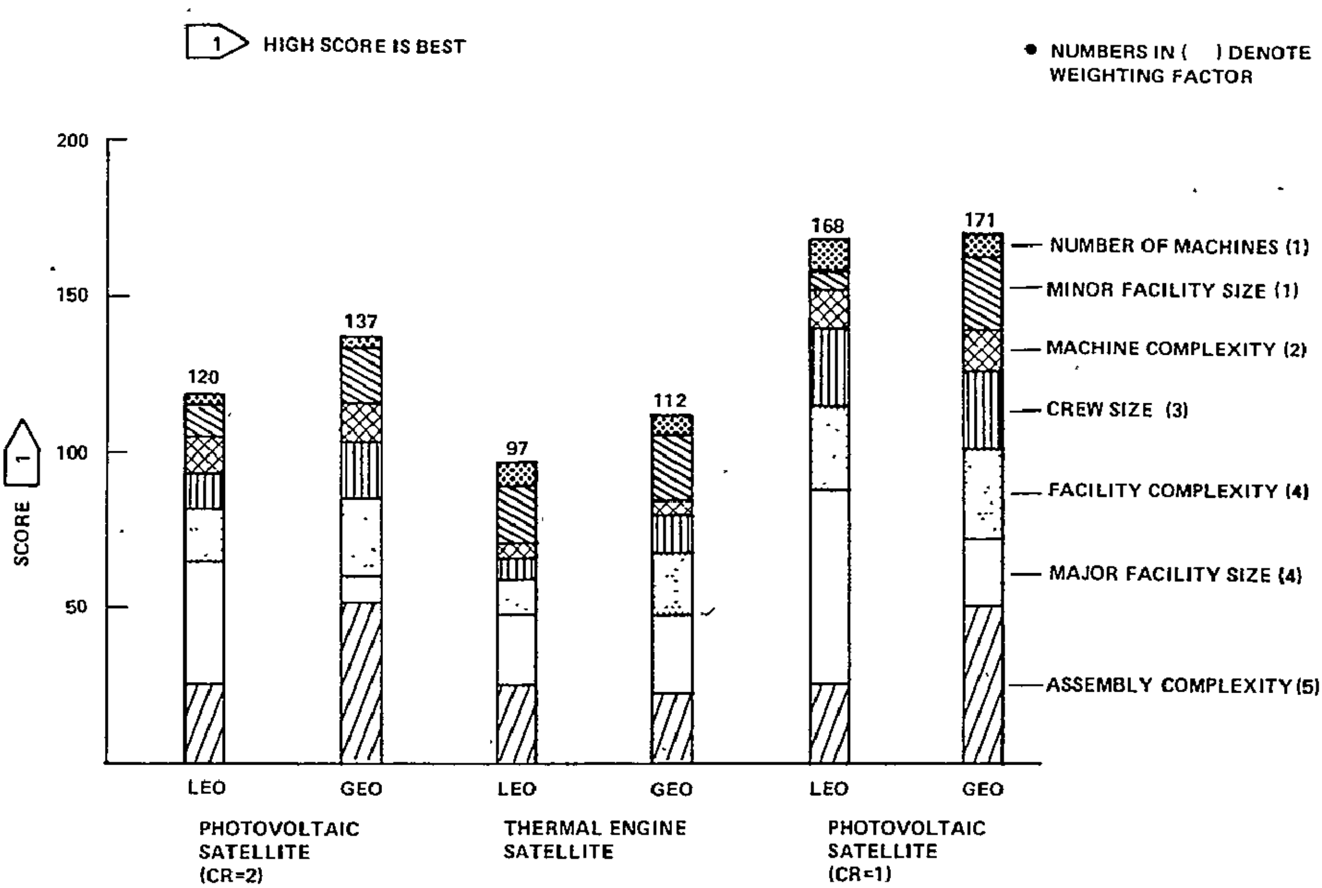


Figure IV-6.- Relative constructability ratings.

Technology Advancement Requirements - Table IV-2 lists those technology advancement requirements considered most significant. The Brayton thermal cycle and the silicon photovoltaic systems appear to have the least development risk with the Brayton being the most advanced, although long-life, leak-free fluid radiator systems will require much development. A continuous solar blanket manufacturing process would be more important to overall system cost than an increase in solar cell efficiency. For example, a 14-percent solar cell manufactured with a continuous production process would make a silicon system very attractive, whereas an 18-percent cell made with today's processes would not allow an economically competitive system.

Environmental Effects Differential Factor - No serious differences in environmental effects were found with any concept. The main factor is launch vehicle emissions that occur only in the launch year. Launch emissions are essentially proportional to SPS mass. A postulated accident with a fire on the launch pad presents some problem with gallium arsenide. There does not appear to be much of a toxicity problem, however, since analysis indicates that arsenic concentrations in any resulting smoke cloud would drop to allowable concentrations very quickly.

ORIGINAL PAGE IS OF POOR QUALITY

TABLE IV-2.- TECHNOLOGY ADVANCEMENT REQUIREMENTS

Photovoltaic			Thermal cycle		
Silicon	Gallium arsenide	Thin film	Brayton	Rankine	Thermionics
Continuous cell/blanket production process	Thin film gallium arsenide application process	Thin film technology	Reliable fluid containment	High temperature metal vapor technology	Thermionic diode technology
		Production processes			
Annealing	Continuous cell/blankets production process			Reliable fluid containment	
	Annealing				

Materials Differential Factors - Gallium is the only material with a potential availability problem. Assumptions for recovery of gallium from various sources influence availability conclusions. Gallium today is recovered from the waste products of aluminum production, and processes are known that could improve the recovery process by a factor of 4. Alcoa stated that more gallium could be recovered if more money is invested in recovery equipment. Production rate capability could be more of a limiter than total reserves. At the present time, availability of gallium does not eliminate the gallium arsenide system as a serious alternative concept.

Energy Conversion Evaluation Conclusions - Conclusions for this study are summarized early in this section. Detailed result and supporting analyses of the energy conversion evaluation may be found in the Boeing final report for Part I, published in June 1977.

b. Solar Cell Technology Status

Contracted study - A small study contract was given to the A. D. Little Corporation to assess various solar cell materials and manufacturing methods, and to identify options that show greatest promise for the development of a cost-effective SPS design. Conclusions of this study indicate that the ERDA National Photovoltaic Conversion Program, although furthering the photovoltaic materials and solar cell production technology, will not meet the development program objectives of the SPS. Valuable information and experimental data are being obtained that are useful for the SPS system and economic studies. However, the goals of the SPS development program are sufficiently different so that an augmented photovoltaic development program will be required.

Considerations based on materials availability indicate that solar cells using silicon should be given the highest priority, with cadmium sulfide representing a potential alternative material. Gallium arsenide solar cell applications may be limited because of gallium availability,

unless low-cost processes are developed to extract gallium from potential sources such as bauxite, fly ash, and oil residues.

Single-crystal silicon will continue to be the leading candidate for photovoltaic arrays for an SPS because of production experience and an extensive data base.

The recommendations from the A. D. Little study are as follows.

(1) Perform research and development (R&D) on candidate solar cells for SPS to achieve the following.

(a) Low mass per unit area

(b) High efficiency

(c) High radiation resistance

(d) Capability of being packaged for subsequent deployment and assembly in orbit

(e) Capability of integration with extended lightweight structures

(f) Processing (e.g., annealing) after prolonged exposure to the space environment

(2) Define and develop processes for space manufacture of solar cells.

(3) Monitor on-going terrestrial cell material development programs and select for indepth evaluation and development those materials that are most promising for SPS.

(4) Establish an on-going orbital test program using the Shuttle for flight testing of candidate solar cells, photovoltaic arrays, and structure-array integration methods.

(5) Establish an orbital program for flight testing of candidate photovoltaic arrays and assembly methods appropriate for the SPS.

<u>In-house assessment</u> - In the past year, considerable progress has been reported in areas of particular importance to the evaluation of the SPS concept. Much of the work of interest is oriented toward terrestrial systems, but, in most cases, the technology has some space applicability. Several areas of particular interest are summarized in the following paragraphs.

Single-crystal silicon cells - A Jet Propulsion Laboratory (JPL) sponsored effort to produce thin (50 micron) silicon solar cells involves thinning wafers sliced from large single crystals at conventional cell thickness by etching to 40 to 80 microns. Though not directly usable for SPS array production, the 11 to 12 percent efficiency achieved and the low

handling breakage loss serve to substantiate the predicted capability to produce a 50-micron SPS cell. Thicker production silicon cells are achieving 14 to 15 percent efficiency.

Silicon ribbon growth - The edge-defined film fed growth process can presently produce a large area of material but with defects that may not allow the quality required for SPS use. However, another process, dendritic web growth, has produced successful prototype production hardware that has the capability of growing webs of uniform thickness in the 100 to 300 micron range. The dendritic-web-growth process shows strong promise of producing large-volume cells of a quality suitable for SPS use.

Polycrystalline silicon cells - The greatest improvement in solar cells in the past year has taken place in the field of polycrystalline cells where efficiencies have been demonstrated in the 10 to 12 percent range (AM1). Early efforts were limited in efficiency because crystal size was small (several microns in diameter), but recent efforts have achieved a larger grain size (millimeters) with a high degree of order. These higher efficiencies, along with their potential low cost and weight, may make polycrystalline cells very competitive as the data base is increased.

Amorphous silicon cells - All the attributes associated with polycrystalline cells apply to amorphous silicon cells with the added potential of lower production costs. Efficiencies in the 5 to 6 percent range have been achieved, and some researchers predict an ultimate efficiency of about 14 percent.

Gallium arsenide (GaAs) cells - Several companies today are making GaAs solar cells with efficiencies of 15 to 16 percent, with the highest reported efficiency being 19 percent air mass zero (AMO). Figure IV-7 shows the rapid progress that one company, Hughes Research Laboratories, has achieved with a 2 cm x 2 cm cell. These high-efficiency devices consist of a very thin active layer (10 micron) on a GaAs substrate which is about 200 microns thick. Because of the gallium availability question, processes must be developed for using GaAs only in the thin active layer on some other suitable substrate.

Cadmium sulfide (CdS) cells - Recent work with CdS cells for terrestrial use have enabled the fabrication of cells approaching 8 percent efficiency. Cadmium sulfide (and other thin films) are appealing because of their potential low cost and light weight, but efficiencies of 11 to 14 percent must be achieved or SPS construction and transportation costs for the larger array area would offset the advantages.

c. Solar Array Design Analysis - Part of the results of the 1976 JSC SPS study was a reference satellite system conceptual design for use in the total system assessment. The reference energy conversion system had a solar array using single-crystal silicon solar cells with a CR=2.

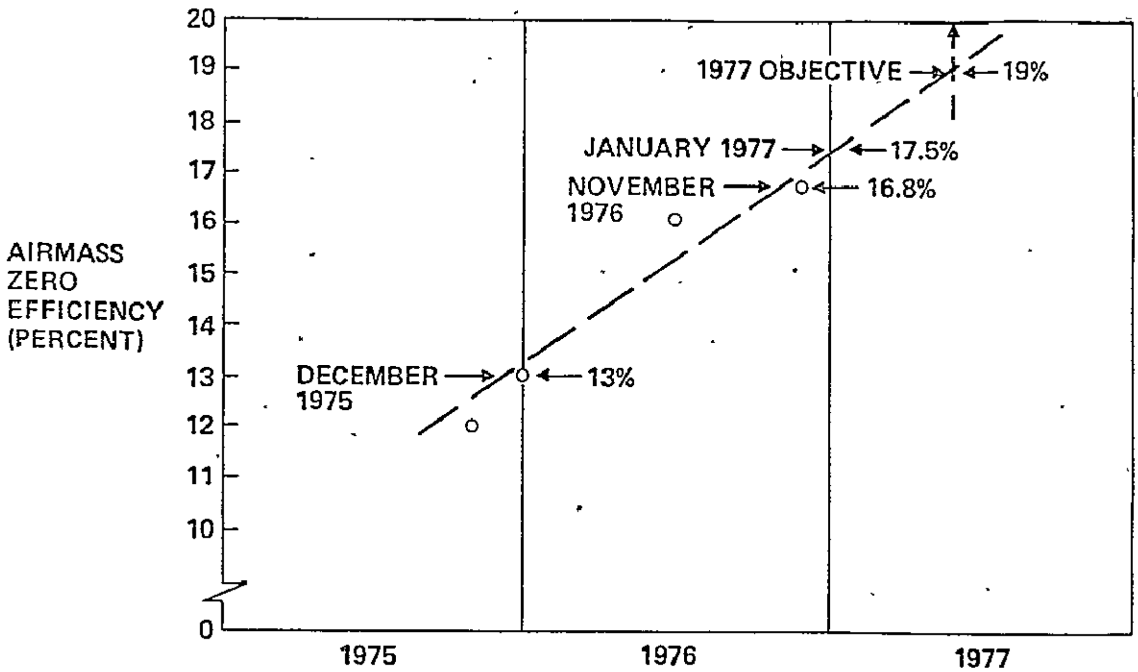


Figure IV-7.- Hughes Research Laboratories GaAlAs/GaAs solar cell efficiency.

TABLE IV-3.- 30-YEAR DEGRADATION ESTIMATE REFERENCE CONFIGURATION (SILICON) ENERGY CONVERSION

Item	Beginning-of-life (BOL)	End-of-life (EOL)
Array output from direct illumination (55° C), W/m^2	188.8	119.1
Degradation due to operating temp at CR=2 (BOL - 106° C; EOL - 89° C), W/m^2	-38.5	-15.7
[a]Array output from reflected illumination (BOL - 106° C; EOL - 89° C), W/m^2	128.5	61.8
5 percent reflector loss from surface irregularity, W/m^2 . . .	-13.9	-9.1
Net increase in output due to concentrators, W/m^2	76.1	37.0
Integrated specific output, W/m^2	264.9	156.1
Effective CR; integrated output/direct input	1.40	1.31
Net efficiency, percent	9.55	5.6

[a]Subject to degradation.

When all factors associated with using concentrators to increase the amount of solar energy on a given cell area were evaluated, a solar array with CR=2 was not as effective as originally estimated. The Boeing data in table IV-3 show that an area ratio of 2 yields an effective concentration ratio of 1.40 at begining-of-life (BOL) and only 1.31 at end

of life (EOL) after 30 years. Data from Project Able indicate a potential 27 percent degradation in concentrator reflectivity after 30 years (neglecting any other loss for Van Allen belt transit). Total system costs for a CR=1 silicon SPS are estimated to be about 4 percent less than for a CR=2 array. The additional design and operational complexity of the CR=2 system make the unconcentrated system the better study choice at this time.

2. High Voltage/Space Plasma Interaction

The 1976 JSC SPS study activities recognized two fundamental spacecraft/plasma interaction phenomena that could occur in geosynchronous orbit. Spacecraft charging, due to the so-called "magnetic substorms," is of concern to the SPS concept definition and is receiving considerable attention through a combined Department of Defense/NASA Program. It is anticipated that solutions, or at least approaches to solutions, will be developed through this activity. The second, the interaction with the quiescent plasma, was not explored in any detail because of study priorities and in recognition of the (presumably) minimal severity of the problem at geostationary altitudes. However, with the advent of the concept of a LEO SPS test article and possible self-powered transfer, the problem is greatly magnified because of the increased plasma density at the proposed operating altitudes (300 to 500 km).

When a potential is applied between different parts of a spacecraft, the conductor and return busses in this instance, the charged particles in the ambient plasma are attracted to the part of the vehicle with the opposite polarity. This current loop through the spacecraft represents a power loss with the magnitude being a function of the applied potential. Insulation of the metallic conductors to minimize the current circulation would seemingly offer a straightforward approach; however, experiments have shown that electric fields generated by virtue of the applied voltage serve to attract the charged plasma particles to the insulator surface, thereby greatly increasing the voltage gradient across the insulator. If high enough, the gradient will exceed the rupture strength and accelerate the reaction. Any breakdown or damage that permits electrons to stream through the insulator will result in further erosion and damage to the material in the localized vicinity of the rupture. Another interesting phenomenon is the yet-to-be-explained dependency of the leakage current on the area of the insulation surrounding the hole. This phenomenon is referred to as a "funneling" effect where the insulator is conceived to play an active role in increasing the current flow by orders of magnitude over what would otherwise be expected.

Before drawing inferences from these data, specific array voltage levels need to be examined. An operational photovoltaic SPS would be electrically configured to operate at about 20 kV dc or 40 kV dc for dc-RF conversions with amplitrons or klystrons, respectively. Predictions have been made of large leakage power losses from high-voltage arrays below those levels (for LEO operation). One example is cited wherein an array in LEO with 10 percent exposure of conductor (bare interconnects) would leak more power than the array could generate at a +16 kV level. The key here is that the

assumption of a positive potential (electron collection) may not be rigorous since the array voltage will float to maintain compatibility with the environment. For example, a 20 kV array in LEO could stabilize to -15 kV and +5 kV. This means that the current flow, if it occurs, will be primarily from collection of the more massive slow-moving positive ions and any leakage current would be expected to be significantly reduced. Experimental data bear out the reduced leakage current for negatively biased electrodes.

Because of the presumed negative voltage bias across the array and the fact that the surface area of the power busses is small (even assuming flat-sheet conductors) compared to the array area, the relative power leakage from the distribution system will be of little significance even at high voltage levels. A more serious concern would be localized arcing to an adjacent part of the spacecraft at a different electrode potential. This possibility can be minimized by maintaining adequate separation between conductive paths and the use of additional insulation in areas with critical separation dimensions.

If the plasma problem or some other requirement on the power module were to dictate a low-voltage power supply availability for LEO SPS tests, the power processing and distribution system could be mechanized to include a dc-dc converter to boost the collection voltage from a few hundred volts to the voltage level required by the dc-RF converters. Such devices could be built at about 1 kg/kW (2.2 lb/kW) for 100-watt converters. It is anticipated that converters up to 50 kW can be developed near this weight-to-power ratio which could operate at 95 to 97 percent efficiency.

3. Structural Considerations

The space-constructed triangular truss has been the primary structural member studied in the past for use in the automated construction of an SPS. However, alternative candidates have been studied which could provide automated construction capability. Figure IV-8 shows a test model of a structural member which could be constructed from coils of rods. This isotropic cylinder, whose surface consists of an open gridwork of equilateral triangles, is efficient in reacting axial, torsion, bending, or shear loadings and is configured to take advantage of the orthotropic stiffness of uniaxially reinforced composite rods. The structure consists of a set of longitudinal rods attached to two sets of over-wrapped helical rods which are wound in opposing directions. The longitudinal rods can be placed outside, inside, or between the helical rods. Since the rods can be joined by welding, the only debris occurs if the ends have to be trimmed. High length-to-radius-of-gyration ratios have been calculated for this type of structure.

Figure IV-9 shows a tooling concept which could be used to fabricate this structural member. The three sets of coiled rods are stored in freely rotating, nested concentric containers which are attached to a powered tool consisting of three concentrically rotating rings which contain rod guides and feeding rollers. Automatic welding apparatus attached to the inner and outer rings weld the rods together as they emerge from the tool.

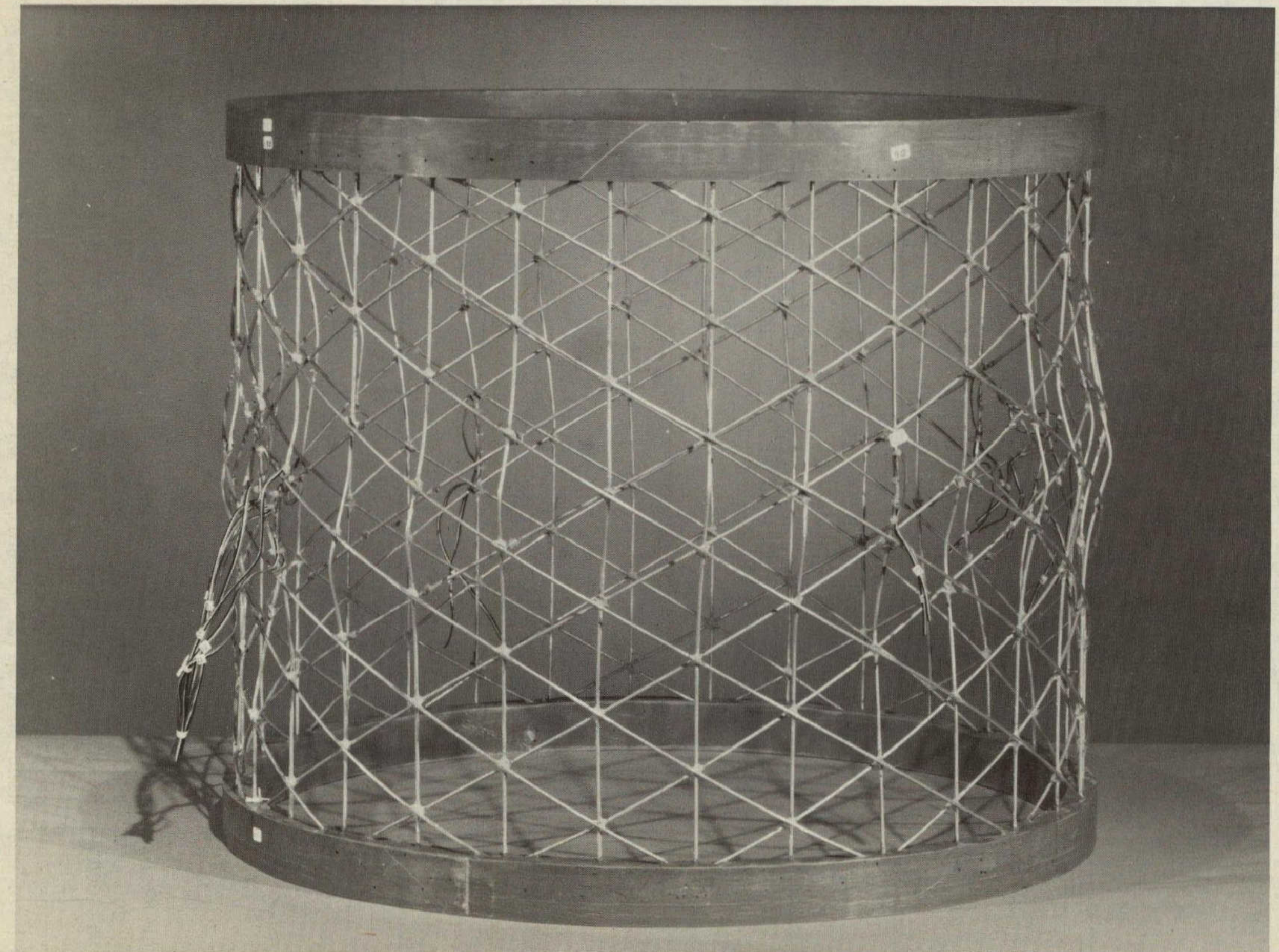


Figure IV-8.- Isogrid test article.

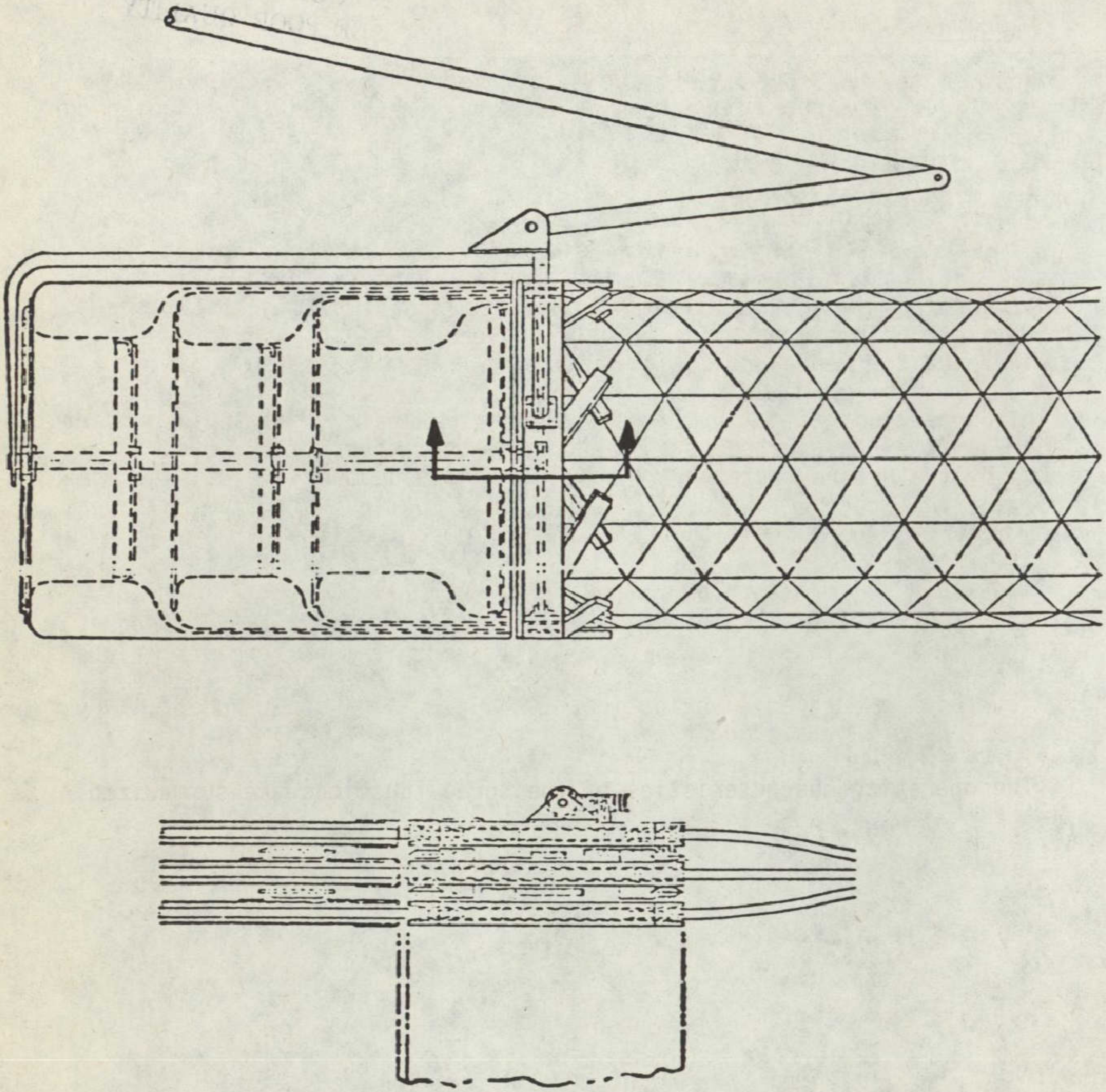


Figure IV-9.- Isogrid cylinder fabricator.

The model shown was made of 2017 aluminum alloy round wire, but the member could also be made from graphite-reinforced thermoplastic resin. Joining techniques would have to be developed to determine the fastest and most energy efficient method of welding the thermoplastic rods at their contiguous intersections. Ultrasonic, thermal, and electromagnetic processes have been used on similar materials, but the best method for this application has not been established.

C. Microwave Power Transmission System

Work on the MPTS falls into two major areas — system analysis and system design. Several specific problems in each area have been investigated during the past year.

1. Microwave System Analysis

Microwave system analysis has concentrated on the examination of various options not considered in the previous study. These options were (1) other transmit antenna illumination functions, (2) smaller SPS sizes, (3) multiple transmit antennas (cluster concept), and (4) performance requirements for mechanical pointing of the transmit array.

Antenna Illumination Functions - The power density distribution over the transmit array aperture should maximize the amount of RF power intercepted by the ground rectenna and minimize the sidelobe levels. The previous analysis used a truncated Gaussian distribution with a 10 dB taper, which is a good approximation of an optimum distribution.

Two other illumination functions, the cosine on a pedestal and the quadratic on a pedestal, have been investigated and their performance compared to the truncated Gaussian distribution. The performance calculations were carried out using the same error parameters that had been applied to the Gaussian distribution. Each function was optimized independently before comparisons were made.

The operating characteristics of the three functions are summarized below for a rectenna radius of 5125 meters.

	Gaussian	Cosine	Quadratic
Collection efficiency, percent	87.76	87.95	88.23
Maximum power density at rectenna, mW/cm^2	22.0	20.8	21.0
First sidelobe referenced to main beam, dB	-24.7	-30.9	-28.7
Maximum power density at transmit array, kW/m^2	20.88	27.61	25.15

Considering the two constraints for maximum power density in the transmit array and at the rectenna, the Gaussian taper has the best overall performance. If the efficiency of the microwave converters can be improved, reducing the thermal problem in the transmit array, the quadratic distribution should be considered. At this time, however, the Gaussian distribution is the most viable candidate.

System size - Initial sizing of the SPS was 5 GW of dc power out of the rectenna based on power density limits at the transmit array and the ionosphere and the desire to maximize efficiency and minimize cost. However, smaller unit sizes would require smaller investment per satellite, produce lower sidelobe levels near the rectenna, and might be more easily handled by utility companies, although the cost of power would be increased.

Microwave frequency is another tradeoff consideration. Previously, the industrial, medical, and scientific (IMS) band at 2.45 GHz was used because of noninterference with communications and the low atmospheric losses at this frequency. There is another IMS band at 5.8 GHz that would require much smaller rectennas, although transmission efficiency is badly degraded during adverse weather conditions.

End-to-end microwave transmission efficiencies were determined for smaller systems operating at 2.45 or 5.8 GHz. The following ranges were used.

Ground dc power output - 1 to 5 GW

Transmit antenna diameter - 0.5 to 2 km

Rectenna diameter - 3.8 to 12 km

Rectenna conversion efficiency - 77 to 90 percent

The results are summarized in figures IV-10 and IV-11. The "63 percent baseline efficiency" represents a 1 km, 5 GW SPS with a constant 90 percent RF-dc conversion efficiency. It is concluded that:

a. Reduced power levels are only slightly less efficient.

b. Antennas of less than 1 km diameter at 2.45 GHz or 0.75 km at 5.8 GHz are not practical because of lower efficiency.

c. Larger transmit antennas reduce rectenna area and sidelobe levels.

d. 2.45 and 5.8 GHz produce similar end-to-end transmission efficiencies at lower power levels.

e. Primary advantage of 5.8 GHz is reduced rectenna area (1/5).

Cluster Concept - In the cluster concept, a large SPS is divided into a number of small, structurally separate subsatellites, including segmented transmitting antennas. To evaluate the rectenna collection efficiency of segmented antennas, a triangular cluster of three antennas was analyzed. Each antenna was 576 meters in diameter, so that the total area equalled that of a single 1-km diameter antenna, and each had a 10-dB Gaussian taper. The three antennas were phased together.

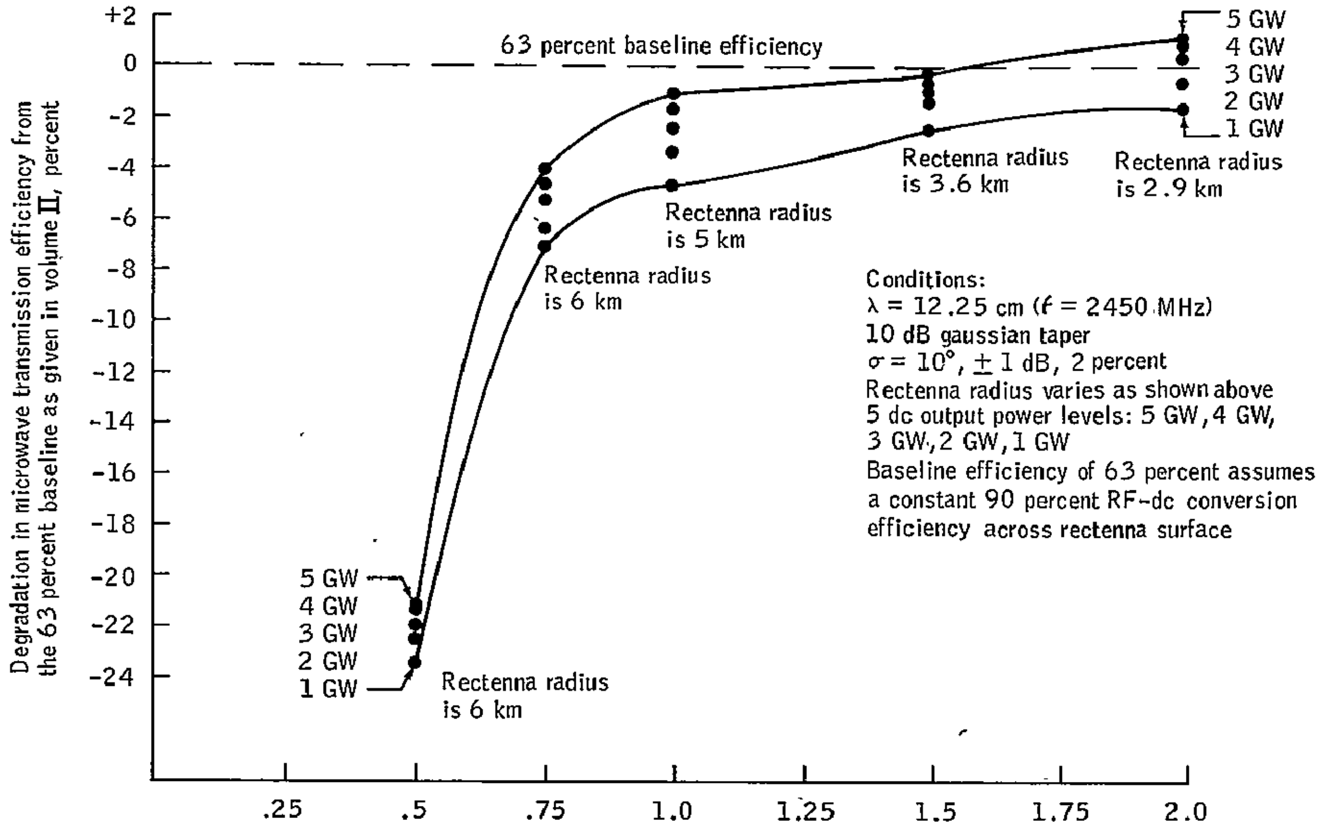


Figure IV-10.- Transmit array diameter (km).

The collection efficiency is shown in figure IV-12 for a separation of 1 km and is greatly degraded relative to a single large antenna because of high sidelobes and grating lobes. The amount of degradation varies with the size and spacing of the antenna segments, but is such as to make the concept unattractive.

Antenna Pointing - Mechanical pointing of the transmit antenna has two aspects - pointing of the antenna as a whole toward the rectenna and pointing of each subarray relative to the antenna. In this study, pointing of the antenna as a whole was investigated for its influence on collection efficiency. Subarray alignment was assumed to be perfect.

The results indicate that pointing errors up to 7 arc minutes produce only 1 percent degradation in collection efficiency, but that 15 arc minutes should not be exceeded because the system would probably be shut down with errors of this magnitude.

2. Microwave System Design

As a result of the previous in-house study, it is recognized that the microwave system would require development in three major areas. These are the microwave generators, the phase control system, and the transmitting antenna array and subarrays. In-house and contract investigations have continued as outlined in the following paragraphs.

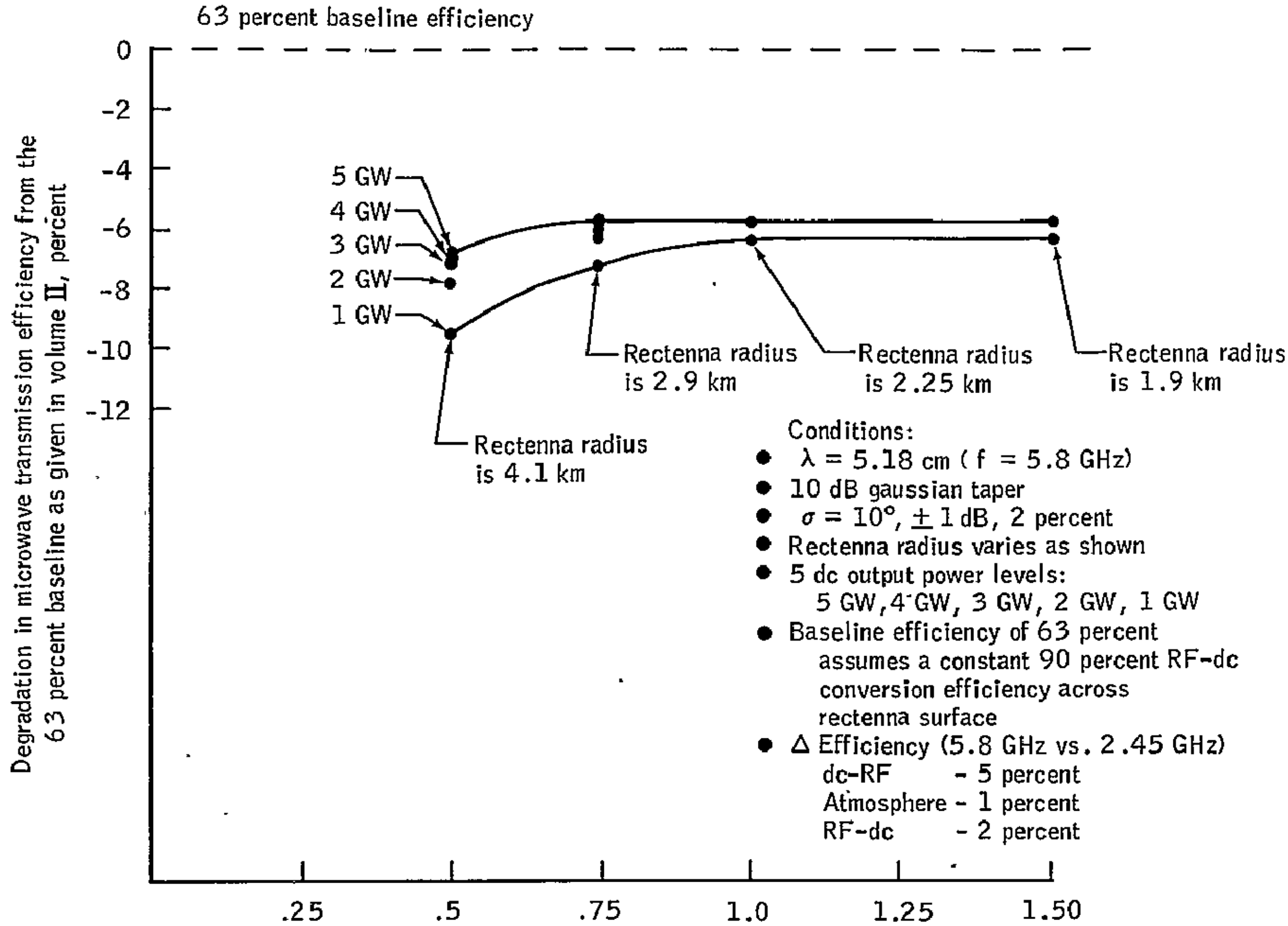


Figure IV-11.- Transmit array diameter (km).

Microwave Generators - In addition to coordinating with Lewis Research Center (LeRC) on the work they have contracted on the amplitron, JSC awarded a contract to Varian Associates, Inc., to determine and evaluate the optimum electrical characteristics of an existing 50 kW klystron operating at 2.45 GHz. Preliminary evaluation indicates that overall efficiency can be as high as 85 percent if the power output can be kept above 50 kW.

Phase Control - A 6-month study contract was awarded to LinCom Corporation in April 1977 to study MPTS phase control. In this study, three methods of distributing a constant reference phase to the subarrays are being analyzed. Each method is somewhat dependent on a symmetrical geometrical layout of components. Two arrangements of subarrays on a square antenna have been identified that provide the required symmetry. Advantages and disadvantages of the three methods are being identified.

Two other areas under study are phase control of the power amplifiers and the effects of frequency separation between the pilot beam and the power beam. This frequency separation has the effect of pointing the power beam at an angle away from the pilot beam.

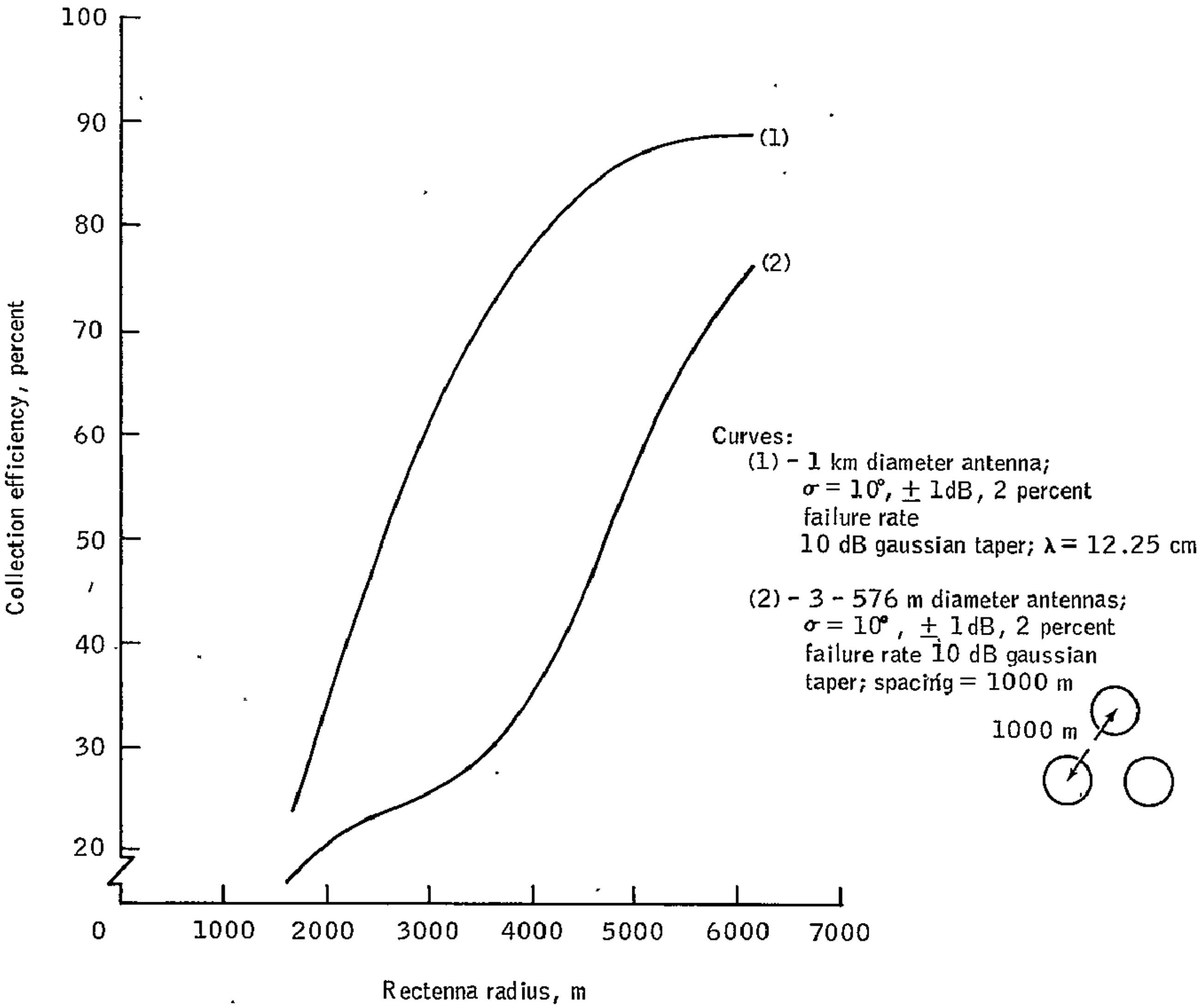


Figure IV-12.- Collection efficiency for a one-solid and a three-segmented antenna.

Structure - Activity has been concentrated on an MPTS structural concept more amenable to construction than that originally proposed. The new concept is a hexagonal planar truss composed of repeating tetrahedrons (tetratruss) as illustrated in figure IV-13.

In this concept, a two-tier arrangement is used that consists of a coarse primary structure, composed of 130-meter-long elements, and a smaller planar truss of similar construction filling each of the 61 triangular spaces in the primary truss.

A contract with the Boeing Aerospace Company was used to develop two "building block" deployable structural elements which can be used in a variety of structural configurations. The contract also reported an application of these elements to the tetratruss concept.

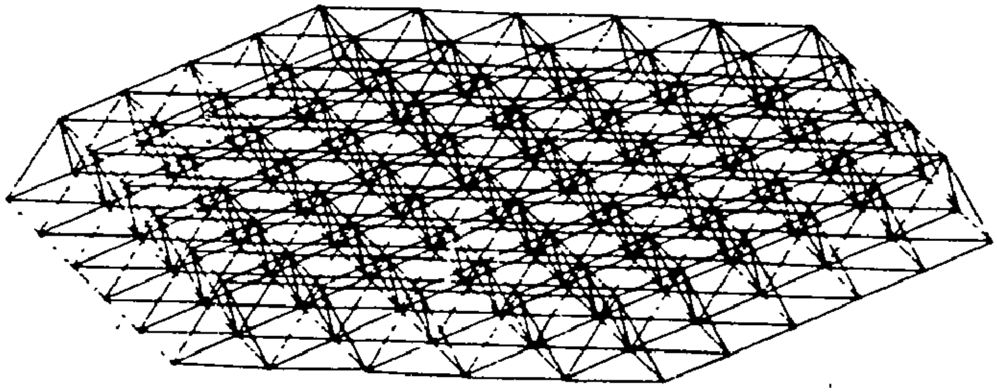


Figure IV-13.- MPTS antenna — tetratruss model.

Another contractual effort has been initiated to investigate the flatness achievable in the tetratruss antenna to determine whether the initial flatness of the second-tier structure will meet microwave transmission requirements, and whether active figure control is required.

A NASTRAN model of the tetratruss was prepared in-house for study of its dynamic characteristics. It was found that natural frequency varies relatively little over a large range of structure-to-total-mass ratios, indicating that additional structural mass is relatively ineffective in increasing structural stiffness.

Microwave Generator Thermal Analysis - A preliminary analysis was conducted to establish microwave generator radiator mass requirements as a function of output power and efficiency. Pyrolytic graphite was used as the radiator material. A comparison of passive radiators and heat-pipe radiators was also made.

Using Raytheon data for amplitron radiators and an estimated 85 percent efficiency for both the amplitron and klystron, it was found that the klystron can use a lighter radiator per unit output than the amplitron. However, structural stiffness requirements and attachments were not included in the analysis for the klystron; so this comparison must be considered preliminary.

The analysis also indicates that a rectangular radiator would be lighter than a circular radiator at the same temperature. For example, a 50-kW klystron requires a passive rectangular radiator of 1.0 kg/kW, or 1.6 kg/kW for the circular configuration.

It was found that a significant weight saving could be achieved by using heat-pipe radiators for klystrons except for low power and high efficiency. At 50 kW and 85 percent efficiency, for example, the passive radiator is about 15 times the weight of the heat-pipe radiator, although the radiator area is comparable.

D. Microwave Reception and Conversion System

1. Rectenna Power Collection

A Rectenna Power Collection (RPC) computer program has been developed which provides the capability to quickly determine the amount of microwave power incident on each row of a rectenna and total incident power. Input variables include rectenna size, beam taper, size of rows, etc. This program has been utilized to generate preliminary current-per-row requirements in support of the structural design study and for preliminary conductor weight and power loss estimates. It has also provided the data base for initial inputs into the economics program in an effort to determine preliminary cost effect of rectenna size variations with fixed microwave power.

Much of the mathematical groundwork and programming techniques have been established so that the RPC program might be expanded to include all actual operational aspects of the rectenna such as dipole and dipole efficiency variations with distance and all interconnection and conversion losses up to the power grid.

The RPC program is available for use in support of SPS rectenna design and costing efforts. The output is compatible with the "Cost of Power from Satellites" program. A short term investigation of the cost effect of rectenna area variation has been conducted. For example, results indicated that a 10-percent reduction of rectenna area results in a cost increase of only 0.35 mill/kWh.

2. Grid Interface

In the definition of the interface between the rectenna and a utility grid system, the following factors involved in the commercial utilization of electrical power from space were identified and evaluated.

1. Daily and seasonal power demand profiles of the grid

2. Throttling range of power generation equipment on the grid

3. Eclipses of the solar collectors by the Earth around the dates of the equinoxes

4. Eclipses by neighboring SPS's around the dates of the equinoxes

The combination of ground-based and space-generation systems must be such that the ground-based equipment can carry the demand load during eclipses of the space systems. A key factor in analyzing this combination is the "throttling" range of the grid system since it really determines the margin available for making up the loss of the SPS power increment. The study produced estimates that the average throttle range will be about 64 percent of full load in the year 2025. Table IV-4 shows the results

TABLE IV-4.- NUMBER OF 5-GW RECTENNAS ALLOWABLE ON EACH REGIONAL GRID BECAUSE OF ECLIPSES AT THE EQUINOXES FOR 2025 (NO STORAGE SYSTEM)

Council	Installed capacity (IC), GW	Reserve margin (RM), percent	Throttle range (TR)	No. of 5-GW rectennas[a]	
				Due to eclipse of Earth	Due to eclipse of other SPS's
ECAR	822.5	10	64.2% of full-load to 100% of full-load	53	10
MAAC	453.7	10		29	5
MAIN	470.8	10		30	5
MARCA	249.6	10		30	5
NPCC	482.1	10		16	2
SERC	1225.2	10		70	13
SWPP	555.9	10		36	6
WSCC	1009.6	10		65	11
ERCOT	402.7	10		26	4
Total				364	60

[a]Number of rectennas = $\dfrac{\text{IC}(1 - \text{RM})\ (1 - \text{TR min.})\ \text{GW}}{\dfrac{5\ \text{GW}}{\text{rectenna}}}$

of an analysis to determine the "allowable" number of 5 GW output rectenna systems on a regional and national grid basis. The results indicate that up to 364 5-GW rectennas (1820 GW total) could be accommodated on a national grid without having power availability problems associated with the space system being eclipsed by the Earth. However, if SPS's were spaced over the longitudinal boundaries of the United States, they would shadow each other twice a year at the equinoxes to an extent that a power availability problem might occur with as few as 60 satellites since this type shadowing occurs near peak electrical load time (6 p.m., and also 6 a.m.).

3. Rectenna Structural Support and Ground Preparation

A design study of the rectenna support structure was done by Bovay Engineers, Inc. Eleven configurations using steel structural materials were evaluated for design wind loads of 20 to 30 psf. Comparative assessments were done for aluminum, wood, and concrete structures. It was determined that galvanized or weathering steel support structures would be the least expensive with a cost range of $1.94/ft^2 to $7.32/ft^2 of shaded area for the various configurations, as compared to the $0.45/ft^2 to $2.35/ft^2

range estimated in last year's report. Bovay's cost estimates were based on conventional construction techniques, and a more mechanized approach would probably result in a lower cost. The rectenna structure part of the total system cost developed in last year's study was based on a structure cost of $0.60/ft^2. The same criteria would result in a structure cost of $1.94/ft^2 in the later study. These rectenna structure costs relate to bus bar cost increments of 2.4 mills/kWh and 7.6 mills/kWh, respectively.

V. SPACE CONSTRUCTION AND MAINTENANCE SYSTEM

A. System Definition Study Construction Results

The Boeing SPS Systems Study, Part I, included an analysis of construction requirements and construction concepts for three SPS configurations — a thermal engine and photovoltaics at concentration ratios of 1 and 2 (CR=1 and CR=2). Requirements for construction at LEO and GEO were analyzed and compared for each configuration. Since the objectives of Part I of the study concerned power conversion alternatives evaluation and the development of data related to space construction location, this initial construction analysis was not directed toward developing absolute mass and cost numbers, but was oriented toward construction differences in satellite types and construction sites. Toward the end, the construction analysis developed the following data for each alternative energy version concept and construction location.

Definition of construction concepts

Definition of type of facility to be used

Definition of construction sequences

Definition of time allocations for each major construction task

Definition of functional requirements for the construction machinery

Definition of requirements for the number of each type of construction machine and their operating rates

Number of construction personnel required

For simplification, the assumption was made that each satellite would be constructed in 1 year, machines were given a fixed operating rate, and the number of machines varied to meet the overall 1-year limit. Antenna construction was not analyzed since antennas were common to all alternatives, but time was allocated for attaching antennas to the array structure, and estimates were made for antenna construction crew size.

As the various satellite types were analyzed, a set of underlying principles (objectives, goals, and guidelines) evolved that were incorporated into all of the various construction concepts. The philosophy which evolved from the assembly of these principles could not always be satisfied, but they do represent an initial set of criteria for space construction which has some engineering or operational basis for existence. This "construction philosophy" is summarized as follows.

Concept	Rationale
Facilitized construction	Do not have to build in extra strength (mass) into every satellite in order to support construction equipment
	Construction operations can be decoupled
Decoupled operations	Construction operations should be as independent as possible so that a slow down or stoppage in one operation has minimal effect on others
Major subassemblies in parallel	Fabricate major subassemblies in parallel in separate facility locations so that maximum time can be allotted to each subassembly fabrication
Work from one side	Simplifies machine resupply logistics
	Simplifies personnel access
	Simplifies facility
	Simplifies removing completed satellite from facility
Continuous beams	Continuous beams, whether curved or straight, minimize the number of joints and eliminate the need for some joint plug assemblies
Construction machine tracks	Using tracks for construction machine is preferred to the use of "overhead crane" technique for getting the machines to the desired location
	Machines located closer to work (long booms not required)
	Provides surface to attach temporary beam supports
	Allows independent activity of multiple number of machines (not constrained by number of overhead cranes
Moving beam machines	Placing beam machines on tracks such that the machine backs away from "extruded" beam is preferred over fixed beam machines

Concept	Rationale
	Continuous longitudinal beams can be made (no longitudinal butt joints required)
	Cross frames can be started as soon as longitudinal beam machines pass the joint area
Support the beams	Beams must be supported as they are fabricated to eliminate undesired stress and unguided end positions
Avoid use of free flyers	Machines that free fly are not desired. The satellite components are too frangible to tolerate accidental collisions

Functional requirements for construction equipment types, quantities, and operating rates were defined and estimates were made of the number of direct construction and supporting personnel (fig. V-1 and table V-). The sizes of facilities are compared in figure V-2.

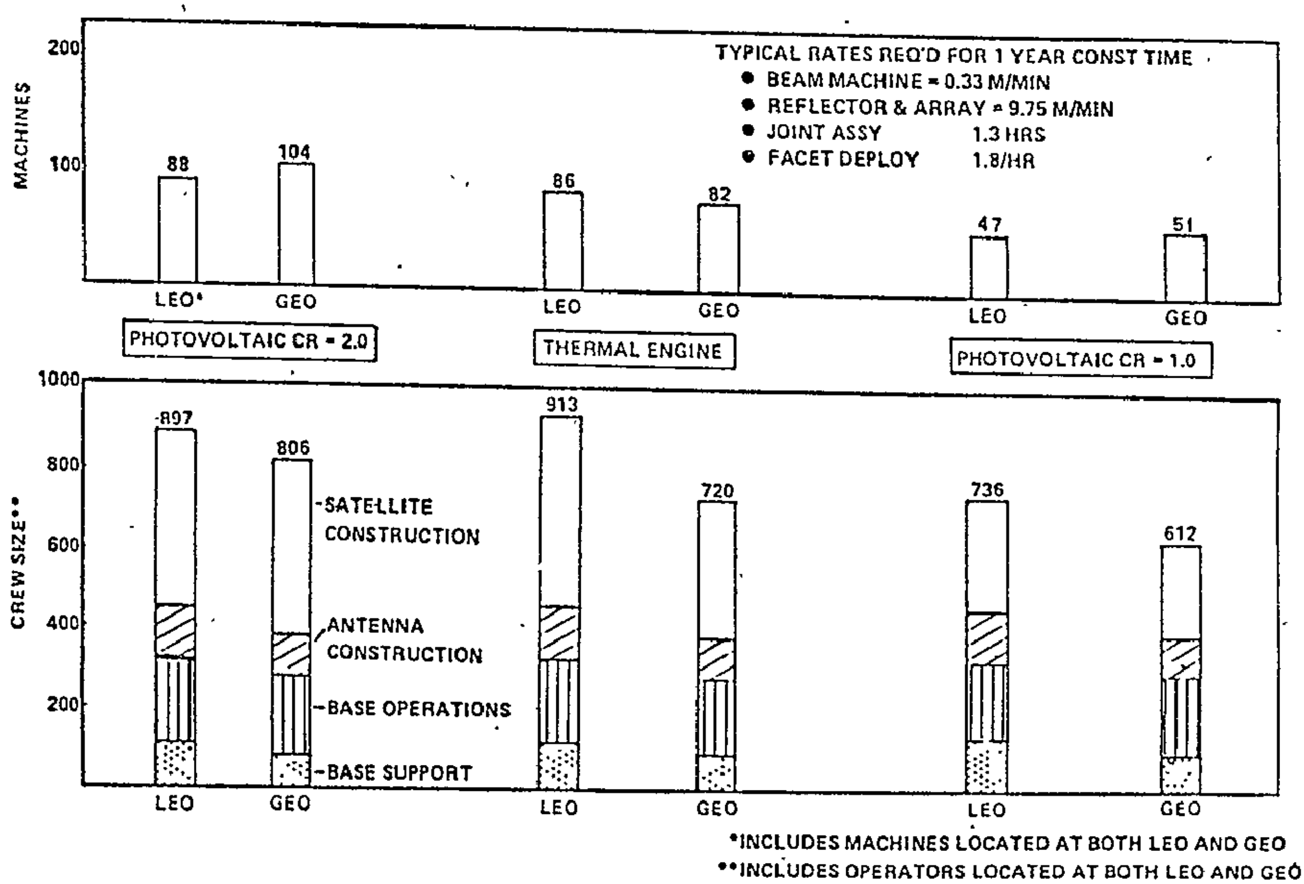


Figure V-1.- Construction machine and crew size comparison.

TABLE V-1.- CONSTRUCTION CREW SIZE COMPARISON

Personnel assignments	CR-2.0 Photovoltaic satellite				Thermal engine satellite				CR-1.0 Photovoltaic satellite			
	LEO construction		GEO construction		LEO construction		GEO construction		LEO construction		GEO construction	
	LEO base	GEO base	LEO base	GEO base	LEO base	GEO base	LEO base	GEO base	LEO base	GEO base	LEO base	GEO base
Base management	(10)	(5)	(5)	(10)	(10)	(5)	(5)	(10)	(10)	(5)	(5)	(10)
Satellite construction	(302)	(135)	(0)	(414)	(337)	(119)		(331)	(186)	(95)	--	(220)
Management	72	22	--	80	21	14	--	21	46	22	--	42
Machine operators	152	32	--	170	146	20	--	140	78	20	--	57
Subsystems	12	15	--	24	30	30	--	30	12	15	--	24
Maintenance	28	28	--	56	68	30	--	68	28	16	--	48
Test and checkout	38	38	--	78	72	25	--	72	22	22	--	54
Antenna construction	(84)	(54)	--	(84)	(84)	(54)	--	(84)	(84)	(54)	--	(84)
Base operations	(138)	(68)	(82)	(124)	(138)	(68)	(82)	(124)	(138)	(68)	(82)	(124)
Management	12	8	8	12	12	8	8	12	12	8	8	12
Data processing	6	4	4	6	6	4	4	6	6	4	4	6
Base maintenance	42	19	19	42	42	19	19	42	42	19	19	42
Transportation	24	10	24	10	24	10	24	10	24	10	24	10
Materials handling	46	19	19	46	46	19	19	46	46	19	19	46
Communications	8	8	8	8	8	8	8	8	8	8	8	8
Base support	(64)	(37)	(23)	(64)	(64)	(37)	(23)	(64)	(64)	(37)	(23)	(64)
Management	7	5	5	7	7	5	5	7	7	5	5	7
Utilities	14	8	2	14	14	8	2	14	14	8	2	14
Hotel/food service	24	12	4	24	24	12	4	24	24	12	4	24
Medical/dental	13	6	6	13	13	6	6	13	13	6	6	13
Safety	2	2	2	2	2	2	2	2	2	2	2	2
Chaplain	2	2	2	2	2	2	2	2	2	2	2	2
control	2	2	2	2	2	2	2	2	2	2	2	2
Totals	598	299	110	692	633	283	110	613	477	259	110	502
Total	897		806		916		720		736		612	

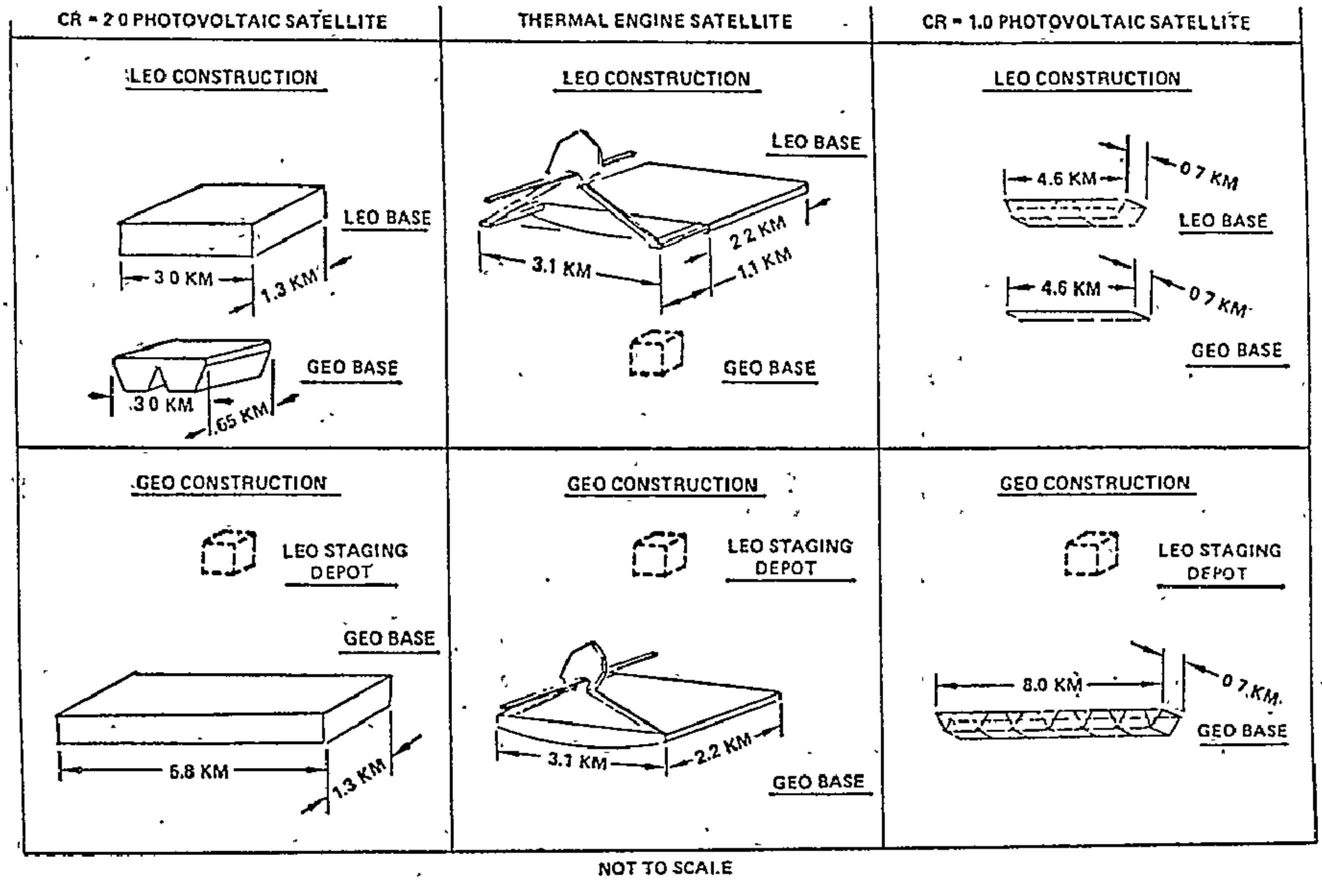


Figure V-2.- Satellite construction facility comparison.

In the Part I study, a preliminary constructability rating was derived for the six combinations of configuration and construction location. Figure V-3 graphically represents the relative values of this rating technique. The parameters used in the rating were given weighting factors to reflect their importance. For instance, assembly complexity was judged to be of the greatest importance. The CR=1 photovoltaic satellite is about 50 percent better from the constructability aspect than the thermal engine satellite. The CR=2 photovoltaic satellite falls in between the other two in constructability rating.

The truss configuration satellites were conceived as a way to simplify construction. Boeing has applied a similar approach to the thermal engine reflector support structure by changing from a parabolic support for the reflector facets to a cylindrical support. This improved construction operations, but increased the facet area requirement by 4 percent. Eliminating the reflectors in changing the photovoltaic to a CR=1 improved the constructability by placing the solar cell blankets on a flat side of the truss structure.

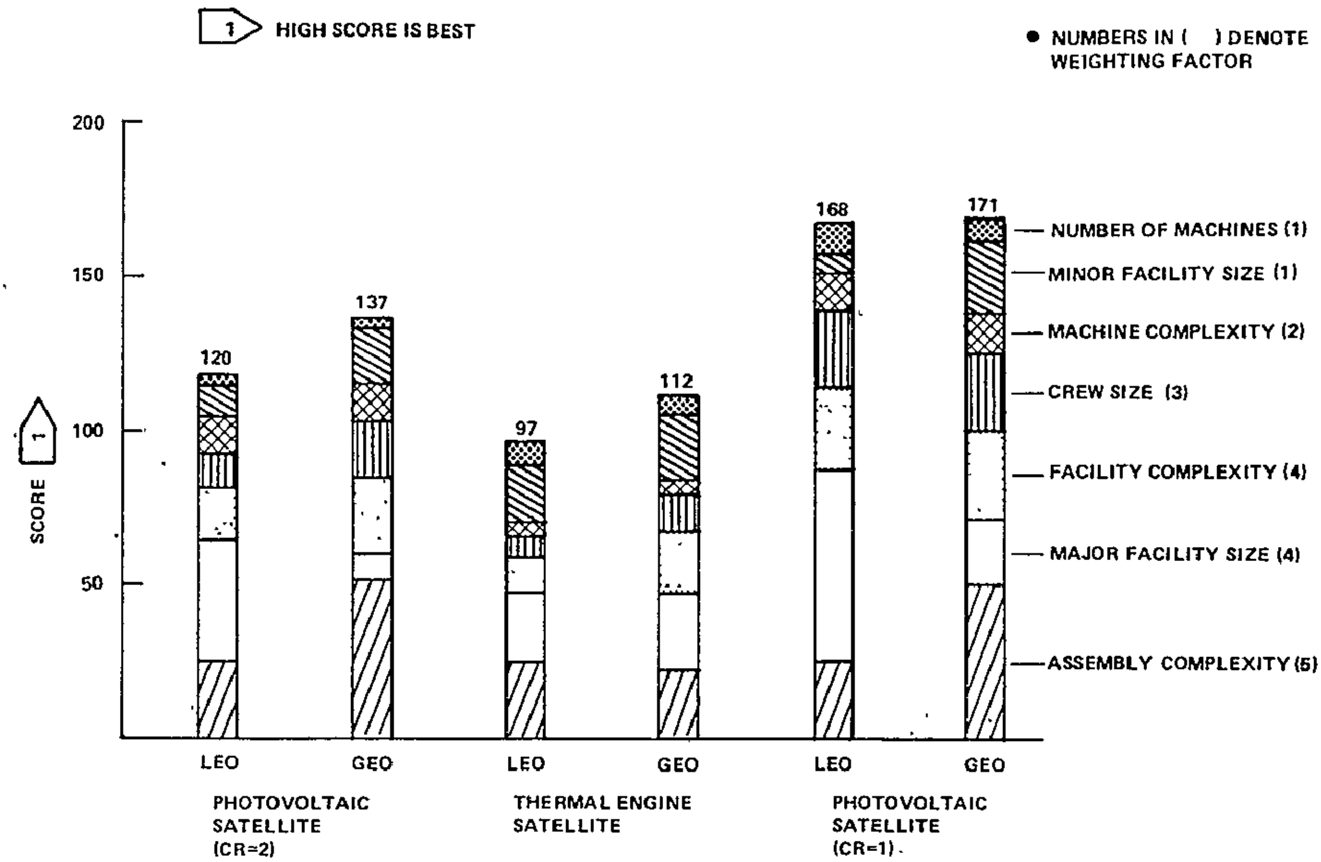


Figure V-3.- Prelimary relative constructability rating.

The rating technique indicates very little difference between the LEO and GEO construction location; therefore, constructability is not considered a strong discriminator in that trade.

Collisions with objects in LEO is a concern during construction. Approximately 30 collisions are predicted during LEO construction and transit to GEO. For 30 years of operation in GEO about 10 collisions are predicted. Boeing estimates that the probability of significant damage to a critical component from a collision is very low. A separate JSC analysis of the collision problem is summarized in section VII.B.

Of greater influence on the LEO/GEO decision is the requirement for berthing the large sections after transport from LEO. A concept for accomplishing the berthing is illustrated in figure V-4.

Another conclusion from the construction analysis is that the assumption of 1 year for construction appears reasonable in terms of machine operating rates, number of machines, and crew size.

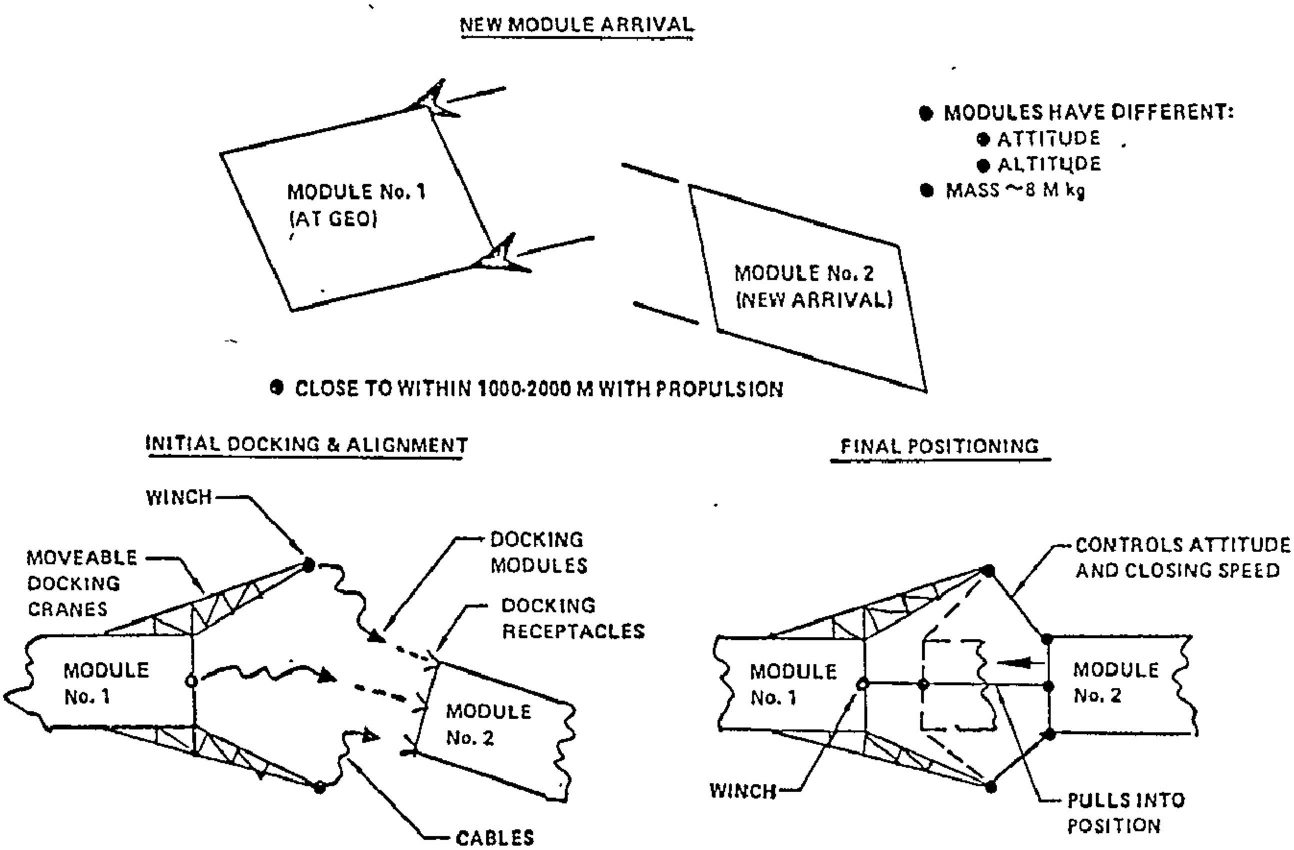


Figure V-4.- Concept for docking/bething large modules.

B. Orbital Construction Support Equipment Study

One of the key areas identified in the "study task structure" of the JSC study report (JSC-11568) for SPS in space was equipment required to support automated fabrication/assembly of large space structures. This equipment has been designated as orbital construction support equipment (OCSE).

To further define the OCSE required in constructing large space systems, a study contract was awarded to the Martin Marietta Corporation, Denver Division under NASA contract NAS 9-15120. The contract span was for 9 months (October 1, 1976, through June 30, 1977). The objectives of the study were to produce a conceptual design and system definition of the OCSE required for orbital construction of large space systems and to derive supporting OCSE development and cost data.

The primary emphasis for this study was directed toward the OCSE needed for support of construction of a large SPS having an operational location in geosynchronous orbit, although the results are applicable to the construction of any large space system. Three SPS baseline configurations were given to the contractor for this study effort. These

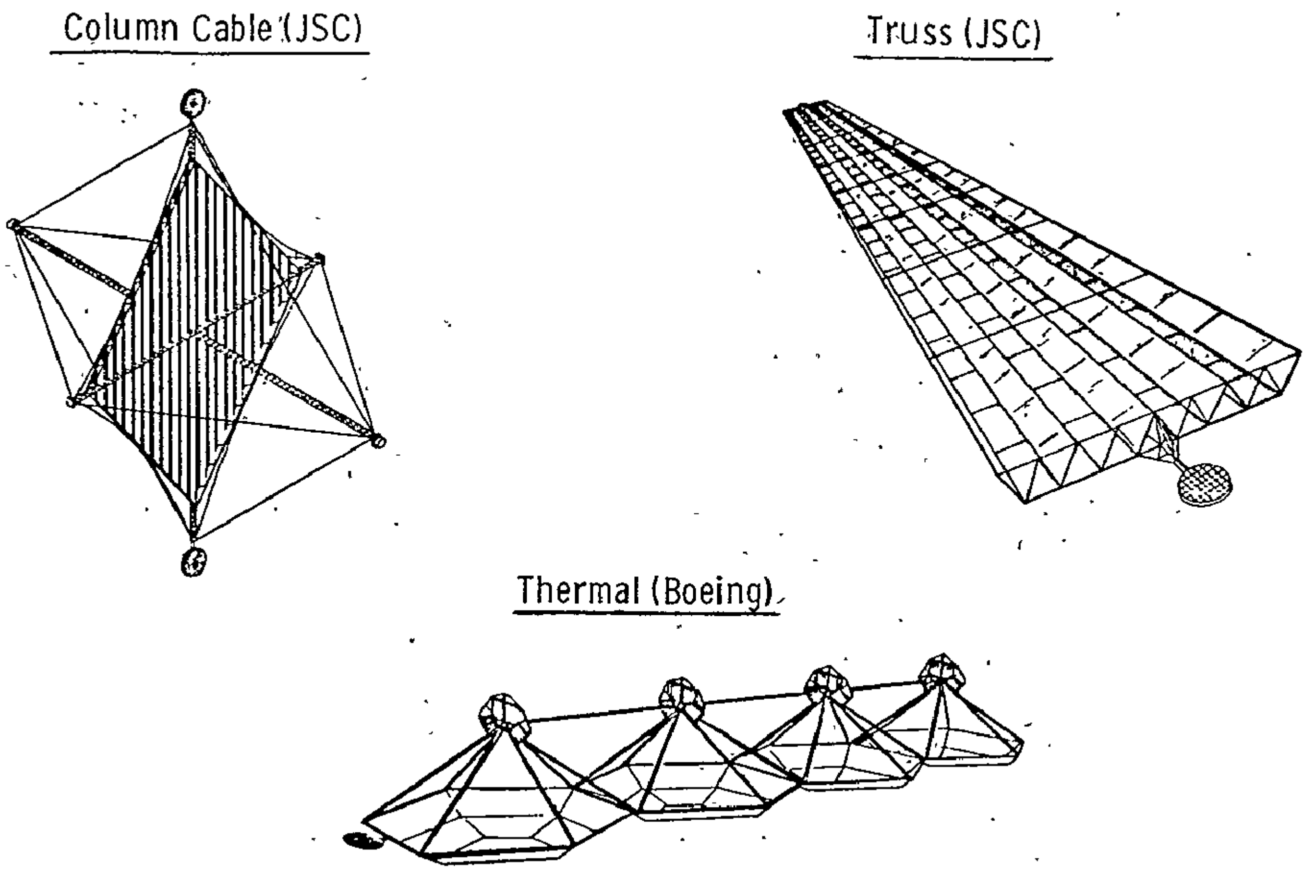


Figure V-5.- SPS baseline configurations.

were the JSC photovoltaic column/cable, JSC photovoltaic truss, and the Boeing thermal cycle concepts. These concepts represent a typical spectrum of present SPS configurations and are shown in figure V-5.

OCSE is defined as that equipment required to support automated fabrication/equipment which will have to be assembled, positioned, set up, controlled, checked out, monitored, serviced, and maintained with specially trained personnel located at the space construction site. It also considers both man and machine in the construction role. The study was divided into three parts. Part I covered OCSE requirements, Part II was concept definition, and Part III included OCSE evaluation and selection.

Based on the construction tasks identified in the functional analysis of the three SPS concepts investigated, requirements were identified for performing the SPS construction tasks on each SPS element. These requirements are summarized in generic process requirements and passes all functions required during SPS construction/assembly. The processes were defined as follows: transport, handle, align, fasten, adjust, monitor, and checkout.

The degree of automated versus direct control of SPS elements was analyzed in terms of frequency of occurrence versus unit mass and frequency of occurrence versus transport distance and handling distance, respectively. Although there was a high degree of scatter evident in the data due to the diversity of elements involved in SPS construction, the data tend to suggest which group of high frequency elements could be accommodated by automated systems and the group of less frequently occurring items which could be more directly controlled.

An OCSE category tree was generated to ensure that an orderly approach was used in evaluating the applicability of different candidate concepts. This structured grouping, as shown in figure V-6, provides a visual reference of candidate similarities by systems characteristics such as operational utility, functional capability, and hardware utilization.

The OCSE lists generated for each SPS configuration contain items that are common to all the configurations. The following summarizes the

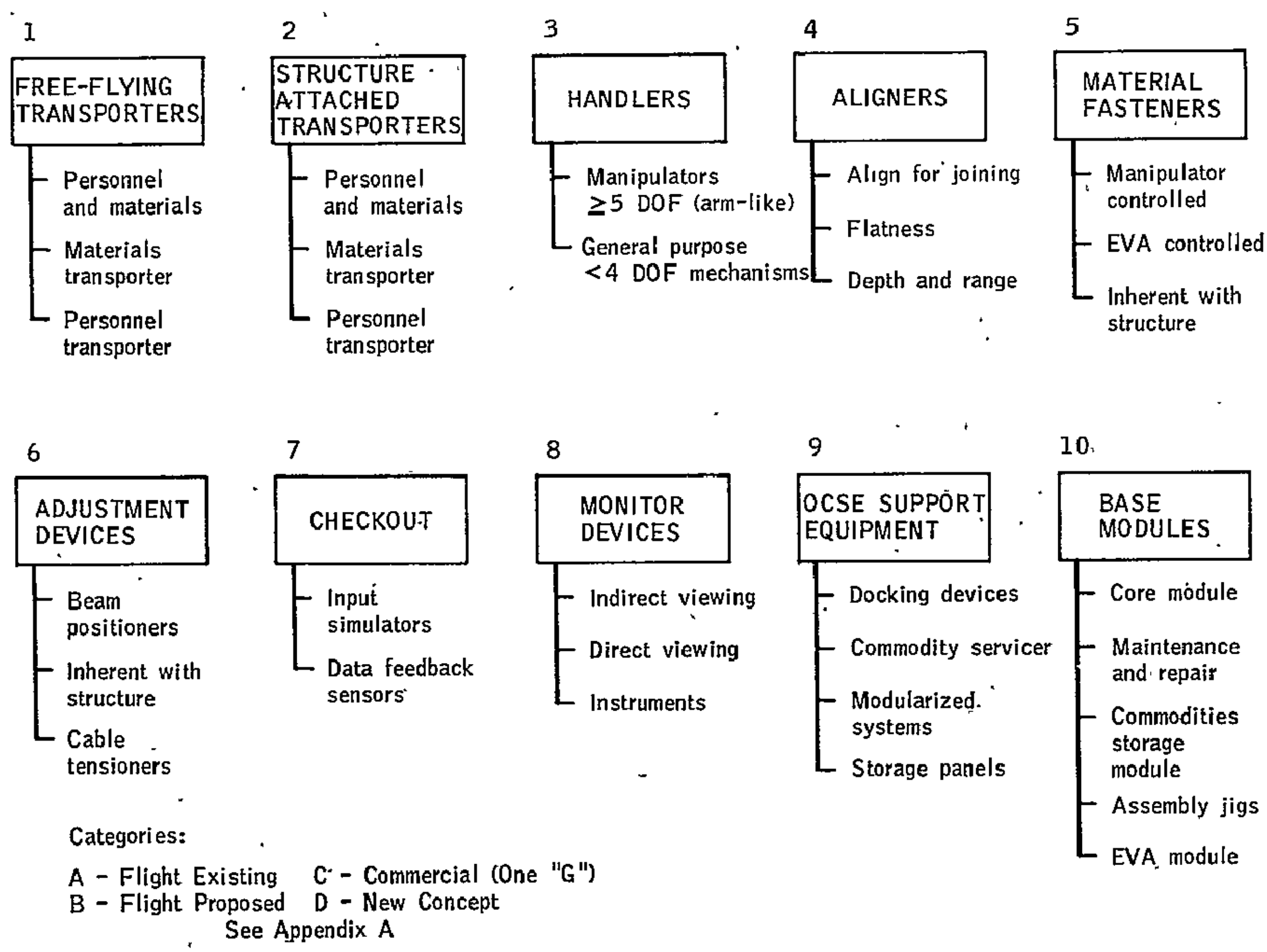


Figure V-6.- OCSE inventory tree.

types of OCSE required.

Transporter, free flying

Transporter, structure attached

Manipulator, mobile base

Manipulator, fixed base

Long boom, attached base

Universal docking device

Aligner (extravehicular activity (EVA), television, and laser)

Fastener (EVA, manipulator, and latch)

Cherry picker

Universal storage panel

Modular systems (guidance, navigation, and control (GN&C)/comm/ACS)

EVA handtools

Monitoring; direct viewing

Servicing module

Checkout system

Figure V-7 shows some of the major concept alternatives as they apply to the OCSE inventory tree established earlier.

A relatively large number of OCSE candidates were identified during the study. Many of the potential candidates were obviously significant to the study and required further detailed evaluation, while others were less significant in both functional and design terms. Therefore, it was necessary to "filter out" less attractive solutions. The OCSE identified was screened and ranked using screening parameters such as task cycles, performance flexibility, performance redundancy, size, interfaces, state-of-the-art, SRT time phasing, potential obsolescence, etc. The screened

candidates resulted in the following.

Manipulator, fixed or mobile base or dual, at least five degrees of freedom

Docking device for joining large systems

Manned cherry picker, attached to booms on structure

Base core module

Fixed-base boom, long/extendable, no more than four degrees of freedom

Maintenance repair module

Commodities storage module

Personnel/material transporter, structure attached

OCSE storage panels

Personnel/material transporter, free flying

EVA module

More detailed results of this study are available in the final report for contract NAS 9-15120 (published by Martin Marietta in July 1977).

C. Automated Construction

Since the SPS must be constructed in space, special automated construction equipment has to be designed and developed. JSC and contractor studies have shown that the primary structure of the SPS will likely be a truss arrangement with one or two sublevels, or tiers, of truss members (i.e., small truss members making up larger truss members, etc.). The basic structural material, relative to current technology, will be composites of plastic resin (thermoplastic or thermosetting plastic) and reinforcing fibers (such as graphite). Required structural properties include low coefficient of thermal expansion and high modulus of elasticity. High tensile strength will be of lesser significance.

The present study construction concept is to use a "beam builder," an automated machine, to fabricate the first sublevel truss structural members from strip stock material that is stored on reels. Thus, all structural material can be transported to orbit as high-density payload. An assembly jig would then be used to position a number of beam builders in the proper location, and support the beams as they are produced to allow joining of the beams to form the final SPS structure. The assembly jig would also provide for installation of all other components of the SPS, including solar blankets, etc. Construction would be automated to that level which is cost effective (i.e., automate unless a manual

- **FREE-FLYING TRANSPORTERS**
  - Personnel and materials
    - Suited, open structure
    - Suited, closed structure
    - Shirtsleeved, closed structure
  - Materials transporter
    - Open structure
    - Closed structure
  - Personnel transporter
    - Suited, open structure
    - Suited, closed structure
    - Shirtsleeved, closed structure
- **STRUCTURE ATTACHED TRANSPORTERS**
  - Personnel and materials
    - Suited, open structure
    - Suited, closed structure
    - Shirtsleeved, closed structure
  - Materials transporter
    - Open structure
    - Closed structure
  - Personnel transporter
    - Suited, open structure
    - Suited, closed structure
    - Shirtsleeved, closed structure
- **HANDLERS**
  - Manipulators $\geq$ 5 DOF (arm-like)
    - Fixed base manipulator long
    - Mobile base manipulator
    - Dextrous manipulator
    - Dual manipulators
  - General purpose $\leq$ 4 DOF mechanisms
    - Fixed base long boom
    - Fixed base telescoping boom
    - Fixed base module remove/replace mechanism
- **ALIGNERS**
  - Align for joining
    - Axis on line
      - Laser
      - Video
      - Mechanical
    - Axis perpendicular
      - Video
  - Flatness
    - Laser
    - Video
    - Transit
  - Depth and range
    - Stereo video
    - Graphic presentations
    - TV reticle
- **MATERIAL FASTENERS**
  - Manipulator controlled
    - Adhesives
    - Welding
    - Mechanical
  - EVA controlled
    - Adhesives
      - Hot melt
      - Ultrasonic
    - Welding
    - Mechanical
      - Punched material
      - Rivets
      - Self-tap screw
      - Clamps
  - Inherent with structure
    - Mechanical (impact, etc.)
- **ADJUSTMENT DEVICES**
  - Beam positioners
    - Manipulators
    - Remote manned vehicle (EOTS)
    - EVA with special tools
  - Inherent with structure
    - Screw jack
    - Linear motion wedge
  - Cable tensioners
    - Turn buckle
    - Cable bender
- **CHECKOUT**
  - Input simulators
    - Heat source
    - Sun source
    - Electrical supply
    - Force and torque
  - Data feedback sensors
    - X-ray welds
    - Ultrasonic
    - Electrical continuity
- **MONITOR DEVICES**
  - Indirect viewing
    - Video - stereo, CCD, etc.
    - Photography
    - Infrared
  - Direct viewing
    - Windows in ECWs
    - Telescopes
  - Instruments
    - Rad fluid leak
    - Contamination monitor
    - Temp indicators
    - Strain gages
- **OCSE SUPPORT EQUIPMENT**
  - Docking devices
    - Vehicle joining only
    - Crew and material
    - Transfer between vehicles
  - Commodity servicer
    - Fluid transfer
    - Module replacement
    - Electrical power resupply
  - Storage panels
    - Manipulator EE
    - Miscellaneous OCSE
    - EVA tools
- **INTEGRATED SYSTEMS**
  - Structure attached mobile manned vehicle with attached manipulators
  - Free flying manned vehicle with attached manipulators
  - Remote manned teleoperator vehicle structure attached
  - Remote manned teleoperator vehicle free flying
  - Subsystem thermal insulator
  - Modularized systems
    - Communications
    - OCSE tracking
    - GN&C
    - Mounting plates
    - Lighting and video
- **BASE MODULES**
  - CHAD module
  - Maintenance and repair module
  - Commodities storage module
  - Assembly jigs
  - EVA module

Figure V-7.- OCSE candidate concepts.

ORIGINAL PAGE IS OF POOR QUALITY

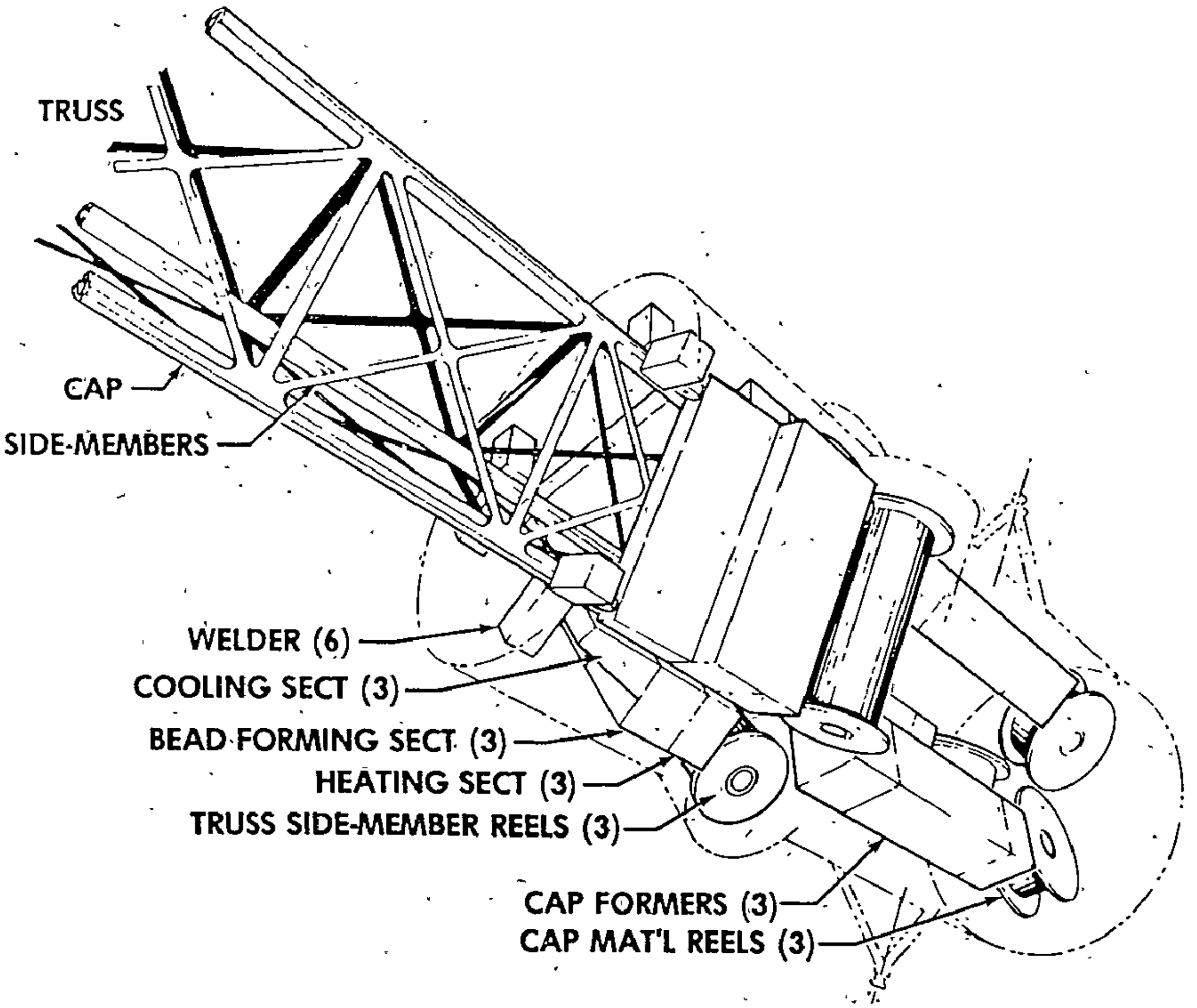


Figure V-8.- Beam builder concept.

operation is lower in overall system cost), or to that point where automation is not technologically feasible. Besides the beam builder and assembly jig, construction equipment will include manipulators (or cranes, positioning mechanisms, etc.), beam joining mechanisms, subsystems installation mechanisms, etc.

The beam builder concept depicted in figure V-8 can continuously and automatically fabricate a triangular cross-section truss of practically any desired length from strip material stored on reels. The strip material is processed and wound onto the reels in an Earth-based operation, and the beam builder can be "reloaded" in space as often as desired. The beam builder concept could use any of several flat strip materials, including aluminum, but the application described here is for an SPS triangular truss made from a graphite fiber-reinforced thermoplastic (such as polysulfone). The truss consists of three cap members

(one at each corner of the triangle) plus side members which interconnect the caps to complete the truss. In operation, a cap is formed from strip material which unwinds from its reel and travels through a heating module where it is heated by radiant electric heaters to its plastic (or forming) temperature of about 320° C. It then travels through a series of matched rollers which form it from a flat strip to a flanged, triangular shape. As it leaves the last of the forming rollers, it enters a cooling section where it is cooled to the "rigid" state (about 135° C) by radiation to cold plates. Now it is a finished cap moving through the beam builder to be joined to the side members. The side members are fabricated from material processed at Earth-based facilities into a flat, patterned sheet and wound onto a reel (three identical reels of material for the three sides). The material is unwound from the reel, heated in the same manner as the caps, and stiffening beads (not shown in the illustration) are formed into the cross member portions by a press forming mechanism which momentarily translates the forming dies to match the velocity of the strip material as it moves through the beam builder. The material is then cooled (radiation to cold plates) and is positioned onto the caps where it is joined to the caps by ultrasonic spot welders. (Ultrasonic vibration produces melting of the thermoplastic at the faying surface with subsequent fusion of the surfaces.)

Precise coordination of the velocity of all members is required to fabricate a "straight" truss member and to avoid "buckling" of a cap member in case that cap is being driven through the forming rollers faster than the other caps. A "closed-loop" type control system employing appropriate sensors, electronics, and servo-mechanisms controls and coordinates the machine operations.

The triangular truss has received the most attention in design studies of automated fabrication equipment, but other types of structural elements, such as the isogrid cylinder described in section IV.B.3, could be adapted for automated construction as well.

VI. SPACE TRANSPORTATION SYSTEMS

A. Systems Requirements and Analysis

To achieve the low launch costs necessary for competitve power costs from the SPS, the launch vehicle should be recovered for reuse with minimal servicing requirements between missions. A large investment in launch vehicle design, development, fleet acquisition, and launch and recovery facilities is anticipated to meet these goals and to achieve the high launch rates needed for the construction of several SPS's per year. Two recovery modes considered last year are still in contention - ballistic recovery utilizing retrorocket braking (perhaps aided by parachutes) and horizontal runway landing of winged vehicles.

SPS space construction studies indicate that 500 to 1000 persons must work in space for 1 year to build each 10-GW SPS. The Space Shuttle Orbiter with cargo bay modifications for transporting from 50 to 100 personnel will be utilized as the personnel launch vehicle (PLV).

Personnel transfer from low orbit to geostationary orbit and return will be required for a significant fraction - approximately one-third - if the primary construction location is in LEO and for approximately seven-eights if GEO construction is selected. The personnel orbit transfer vehicle (POTV) selected will use oxygen and hydrogen (O_2 and H_2) and is expected to utilize two stages for propellant economy. It will be based in LEO. Passenger capacity is 75 persons per trip.

Movement of SPS elements from low orbit to geostationary orbit poses one of the largest technical challenges of the SPS program. Numerous propulsion concepts are under consideration for this mission, including the cryogenic propulsion system of the POTV, scaled up to a size appropriate for transfer of the largest SPS component. Advanced propulsion concepts may provide advantages by reducing the propellant requirements in low orbit. The O_2/H_2 cargo orbit transfer vehicle (COTV) will require approximately two parts propellant in low orbit for every one part SPS payload. Electric propulsion concepts may reduce these propellant requirements by as much as a factor of 10. This advantage is coupled with a set of disadvantages - long trip times (approximately 6 months), relatively heavy and expensive apparatus, complex mission profile, and scar weight and array degradation penalties upon the SPS. Low-orbit construction and use of approximately one-fourth of the SPS module array to provide electrical power to the COTV results in significant (approximately one-third) total transportation cost savings compared with geosynchronous construction of the SPS with O_2/H_2 COTV transfer. LEO construction and electric propulsion "self-power" of SPS modules reduces the required launch rates by half. LEO construction preserves acceptable SPS total transportation costs better than GEO construction with upward adjustments of launch cost estimates.

SPS transportation activities since August 1976 emphasized four areas.

Launch vehicle synthesis at JSC has now identified a two-stage winged HLLV. This vehicle is described in the HLLV section of this report. The reason for altering the JSC 1976 "baseline" ballistic return HLLV was unresolved concern over intact at-sea recovery of very large vertical descent ballistic vehicles. The horizontal-landing winged vehicle is considered to be the more conservative design, given the current state of knowledge. Recent analyses indicate smaller than expected dry mass and operating cost penalties for the incorporation of lifting surfaces.

Propellant supply for the SPS transportation fleet was quantified in the JSC 1976 study and found to be a large absolute value of liquid hydrogen and hydrocarbon fuels. Concerns over continued availability of hydrocarbon fuels in the post-2000 era and difficulty in extrapolating future fuel prices led to an alternate fuels source study. This study, described in volume II, established the feasibility and characteristics of a production facility for all launch system fluids (oxygen, hydrogen, propane, and argon) based upon input streams of coal, air, and water. The launch vehicle flight costs of this report are based on the results of that study.

A third major activity was the SPS transportation system study conducted by the Boeing Company as part of the "SPS Systems Definition Study." Preliminary results indicate that either two-stage ballistic or two-stage winged HLLV's may be developed for less than $10 billion and that the nominal estimate for the launch cost of either vehicle is approximately $20/kg. Total transportation costs were estimated to be approximately $650/kW for LEO construction and $800/kW for GEO construction. The Boeing conclusions available to date are summarized in volume II.

The fourth area is launch site selection. The Boeing study selected an ETR launch with off-shore ship recovery of both stages of the two-stage ballistic entry vehicle. "Texas Tower" off-shore launch pads can ameliorate the launch noise, and sonic overpressures of second-stage return flight may dictate that recovery locations for both stages be far off-shore. However, winged launch vehicles require a runway approximately 200 n. mi. downrange (east) for the booster and a runway for the second stage. A study performed by JSC-WSTF evaluated the use of western U.S. desert sites as a launch and recovery operations complex. This study is included in volume II.

Performance advantages result from the use of low-latitude launch sites in that the required plane change is reduced. Numerous sites may be considered candidates; in all cases, a runway approximately 200 n. mi. east of the launch site and an economical ground transit return of the dry booster are required for the winged two-stage vehicles. A shipborne launch with the industrial area/recovery site located at a harbor on the west coast of a land mass may prove to be an effective approach. Bahia de

Sechura, Peru, is one such candidate site. The San Diego, California, area may be an alternate west-coast site in the continental U.S. (CONUS) but does not enjoy the full benefit of low latitude.

Another SPS space transportation issue has been identified - how to provide effective, large-scale demonstration and development of the SPS concept without a new "clean sheet" launch system. Indications are that launch systems derived from the current Space Shuttle may adequately fulfill that role, for an initial SPS with a rating of up to 500 MW of ground power output. Further definition of early SPS transportation is in progress.

B. Heavy-Lift Launch Vehicle

The HLLV is designed for transporting all SPS freight, except crews and high-priority cargo, and the design requirements are unchanged from the previous study. The launch site is assumed to be the John F. Kennedy Space Center (KSC) or a western U.S. launch site for costing purposes. For performance comparisons, payloads are considered to be inserted into a 500-km, 28.5°-inclination orbit. Payload rendezvous capability is provided by an orbital maneuvering system (OMS), which may also provide orbit circularization (from an approximately 90- by 500-km insertion orbit). The HLLV will provide a payload environment - such as acceleration, shock, vibration, temperature, etc. - similar to that provided STS payloads but will provide no additional services.

The key figure of merit for the HLLV is cost per pound of payload to LEO. Studies of several configurations in the past year have produced concepts in which payload shrouds and interstage structures are recovered. This recovery reduces the cost per flight as much as $7 million. The reuse goal of 300 to 500 flights, determined from a standpoint of structural design and fracture mechanics, is retained and may be used for replacement calculations and costing purposes. An in-depth analysis of parts attrition and predicted operational losses is needed to obtain a more accurate cost-per-flight estimate.

No revolutionary advanced technology was assumed for characterizing the HLLV subsystems, but propulsion and structures characteristics were predicated on evolved 1995 technology. Hydrocarbon-fueled engines remain favored for first stages because of the higher fuel density and consequent reduced structural weight, and hydrogen-fueled engines are chosen for second stages because of the higher specific impulse and reduced propellant weight. The relative cost of hydrocarbon fuels and hydrogen exerts a strong influence on the stage design of both ballistic and winged two-stage vehicles. The HLLV configurations have not yet been optimized, pending improved predictions of hydrocarbon and hydrogen fuel costs.

The three representative HLLV configuration types developed in the 1976 report remain as candidates, but each type has been refined and changed in detail. The current candidate HLLV configurations are presented in table VI-1.

TABLE VI-1.- HLLV CANDIDATE CONFIGURATION CHARACTERISTICS

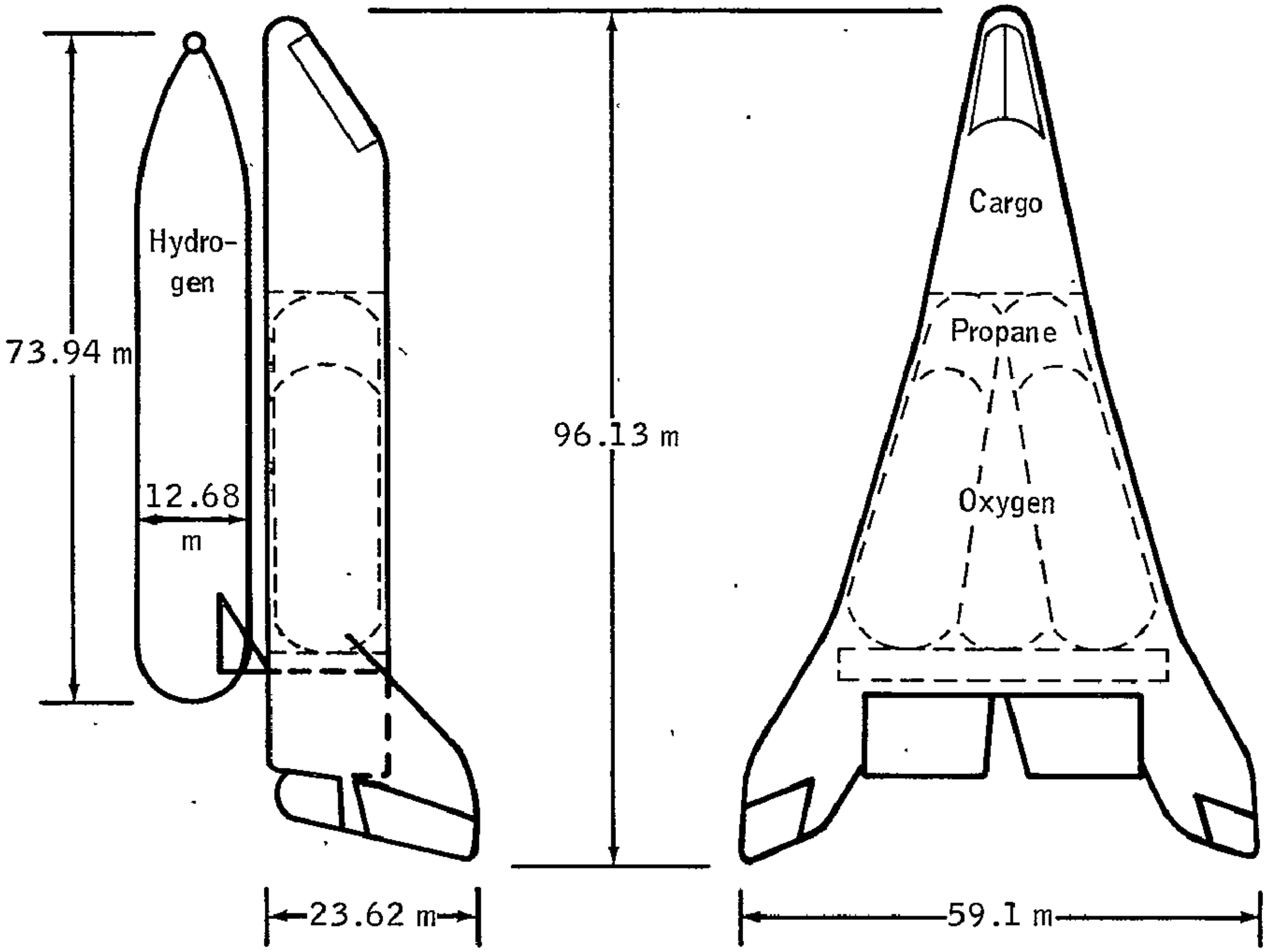
Configuration	Propellants		Payload capacity, metric tons
	Stage 1	Stage 2	
Modified SSTO	O_2/H_2 and C_3H_8	--	455
Two-stage winged (EDIN EX 338-76)	O_2/C_3H_8	O_2/H_2	455
Two-stage ballistic (Boeing NAS 9-15196)	O_2/RP-1	O_2/H_2	390

The modified single-stage-to-orbit (SSTO) is derived from the concept described in the previous study. It differs from last year's version in that the payload is increased from approximately 385 000 to 1 million pounds and the payload is carried in a cargo bay rather than externally in a shroud. Its configuration and characteristics are shown in figure VI-1.

The two-stage ballistic configuration now chosen as representative was developed by Boeing and presented in the SPS Systems Definition Study (NAS 9-15196), Part 1 report. It features a retractable payload envelope that is completely recovered. Its net payload capability is approximately 860 000 pounds, and both stages are recovered at sea. Its configuration and characteristics are shown in figure VI-2.

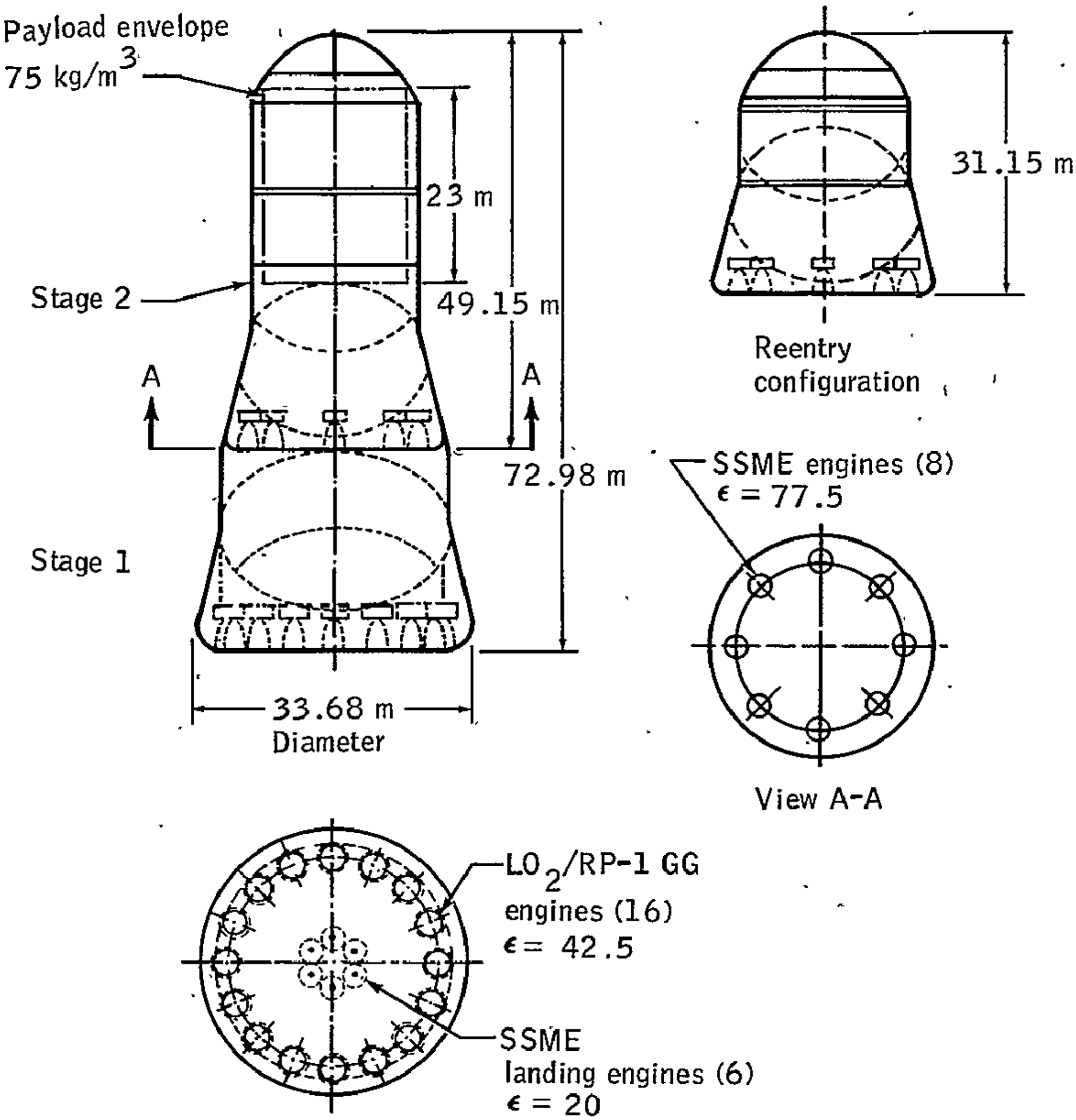
A new JSC two-stage winged vehicle has been defined. It has a net payload of approximately 1 million pounds and is recovered on land. The variation in payload capability with launch site is shown in table VI-2. The vehicle is completely recoverable, including the payload envelope and the interstage structure. Its configuration and characteristics are shown in figure VI-3.

Three independent estimates were made for the cost of launching payloads to LEO with two-stage winged vehicles. Data from the propellant costs study detailed in volume II were used in the two JSC analyses; and, in the third analysis, by Boeing, their propellant cost projections were used. The resulting nominal-cost-per-pound-to-LEO estimates were \$11.00 and \$8.44 for JSC and \$8.64 for Boeing. Boeing did not make low and high estimates; but JSC low estimates were \$6.60 and \$5.25, and the high estimates were \$18.00 and \$10.42. In order to estimate total transportation costs for an SPS program (see section VI.F), low, nominal, and high values



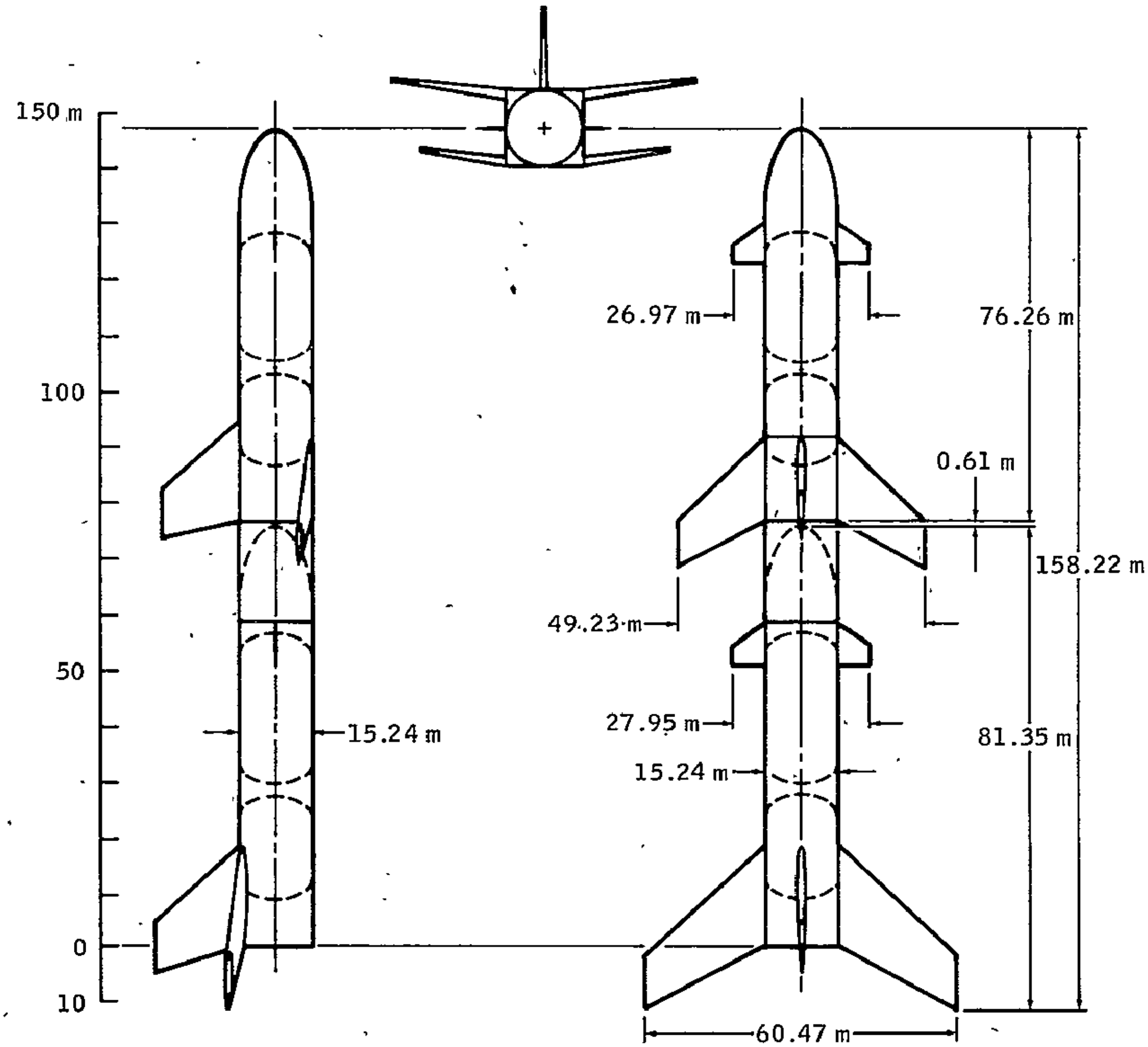
Payload, tons, 500 x 500 km	455
Modified orbiter, inert, tons	726
Stage, inert, tons	772
Stage, oxidizer, tons	8 647
Stage, fuel, tons	1 620
External tank, dry, tons	47
External tank, fuel, tons	565
Gross lift-off weight, tons	12 177
Number of engines	21
Tank staging, altitude, km	111
Tank staging, velocity, km/sec	7.82
Thrust/weight ratio	1.30

Figure VI-1.- Modified single-stage-to-orbit (SSTO).



Payload, tons, 500 x 500 km	391
Stage 1, inert, tons	787
Stage 1, propellant, tons	7 456
Stage 2, inert, tons	359
Stage 2, propellant, tons	1 479
Gross lift-off weight, tons	10 472
Number of engines, stage 1	16
Number of engines, stage 2	8
Staging altitude, km	69.9
Staging velocity (rel), km/sec	2.89
Booster maximum downrange, km	480

Figure VI-2.- Two-stage ballistic HLLV (Boeing).



Payload tons, 500 x 500 km	455
Stage 1 inert, tons	664
Stage 1 propellant, tons	5708
Stage 2 inert, tons	364
Stage 2 propellant, tons	2303
Gross lift-off weight, tons	9589
Number of engines, stage 1	16
Number of engines, stage 2	14
Staging altitude, km	43.9
Staging velocity, m/sec	1.86
Booster down range, km	290

Figure VI-3.- Two-stage winged HLLV (JSC).

TABLE VI-2.- WINGED-LAUNCH-VEHICLE PAYLOAD VERSUS LAUNCH SITE CAPABILITY

Launch site latitude, deg	Launch elevation, ft	Net payload, lb
5.50	0	1 000 000
26.61	0	967 000
32.30	6000	984 000

of \$7, \$9, and \$14 per pound to LEO were selected. (The low estimates were rounded upward, and the high estimates were averaged. The \$18 included operations costs based on ratioing STS manpower requirements, which are considered to be too conservative.)

The range of cost estimates selected is significantly less than the \$10, \$15, and \$25 per pound to LEO used in last year's report. The reduction reflects the use of reusable payload shrouds (which saves up to \$7.00 per pound), a reduction in the estimated cost of hydrogen from \$2.25 to \$0.36 per pound, and some reduction in the estimates of operational costs.

The DDT&E and theoretical first unit (TFU) estimates were all close to \$10 billion and \$1 billion, respectively, for the two-stage winged configuration. Boeing estimated their ballistic configuration would cost approximately 20 percent less for DDT&E and 11 percent less for TFU. This amount is approximately double last year's JSC estimate for the ballistic and the increase is due both to a different vehicle design and different estimating techniques.

C. Personnel and Priority-Cargo Launch Vehicle

The PLV will be used to transport all personnel to LEO and can, in addition, deliver high-priority cargo to LEO on a modest scale. The 1976 configuration selection, which is a modification of the current Space Shuttle vehicle, is unchanged. The Orbiter can be modified to transport passengers in the cargo bay, with a capacity range of 50 to 100.

The payload capability and operating costs of the Shuttle can be improved by replacing the two solid rocket boosters (SRB's) with a liquid rocket booster (LRB) using oxygen and hydrocarbon propellants. A change from the 1976 report is that four LOX/propane engines with a thrust of approximately 2 million lbf, of the type proposed for the HLLV, are referenced rather than the F-1 type of engines considered previously. The

PLV configuration and characteristics are shown in figure VI-4. The range of PLV cost per flight at the SPS required launch rates is estimated to be from $10 to $16 million (1977 dollars).

D. Cargo Orbital Transfer Vehicle

Following construction of the SPS in LEO, a portion of the solar array of the SPS module may be deployed in LEO to provide electrical power during sunlit portions of the orbit. This electric power may be used in ion or arc jet engines to produce thrust for orbit-raising from LEO to GEO.

In the "SPS Systems Definition Study, Part 1" (NAS 9-15196), Boeing reported the results of their systems synthesis and optimization. A 120-cm-diameter ion engine utilizing argon propellant was characterized, on the basis of the LeRC/Hughes development of the 30-cm ion engine using mercury as propellant. The optimization studies indicated that a 5000-sec I_{sp} is the maximum value preferred, with an approximately $5/10^{-5}$ g initial-thrust-to-weight ratio resulting in a trip time of 180 days. A module of a photovoltaic SPS built in LEO was estimated to have a mass of 5560 tons and dimensions of 2.5 by 4.1 km. The thrust level needed was 5600 newtons, in order to provide sufficient control authority to overcome low-altitude gravity gradient torques. This thrust level required approximately 3120 thrusters of the 120-cm size. Chemical propulsion was used for attitude control during the typical 18 percent of the mission duration in which the module was occulted. Twenty-two percent of the total SPS module array and reflectors was deployed, with the result that approximately 200 MW were produced at mission initiation. Conventional single-crystal-silicon solar cells will lose a significant percentage (approximately 40 to 60 percent) of their output during the slow passage through the trapped-radiation belts. Unless radiation-tolerant solar cells are developed or means developed for the annealing of the cells at GEO to restore output, the module may have to be approximately 13 percent larger to arrive at GEO with the desired 1-GW module output intact. The masses involved in beginning the movement of the SPS module to GEO were estimated by Boeing to be:

5560 tons - SPS module (one-sixteenth full, 10-GW SPS)

1000 tons - SPS modification for self-power, including power distribution at 3600 V

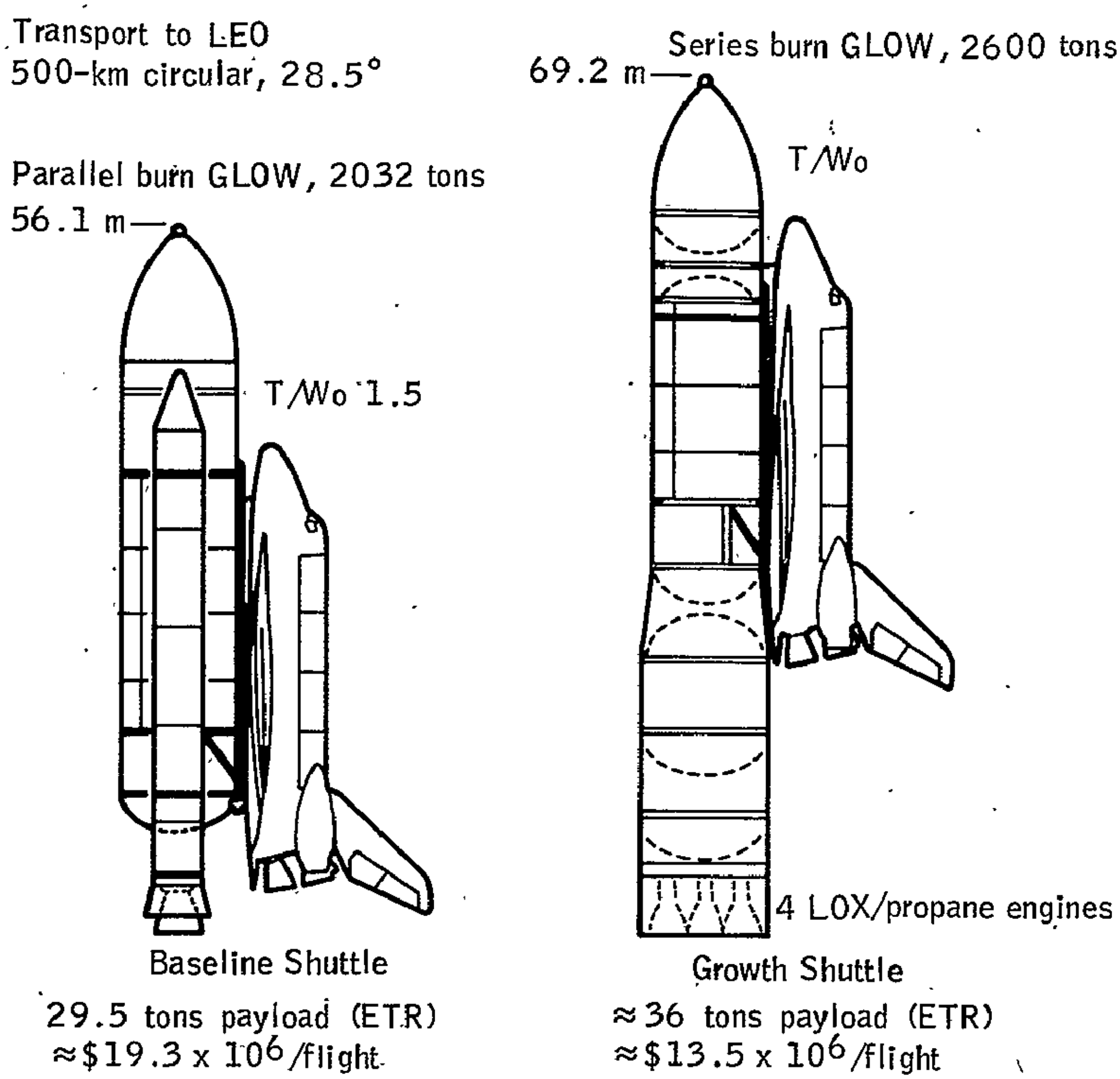
950 tons - propulsive stage dry mass, ion and chemical

1530 tons - argon propellant

400 tons - O_2/H_2 attitude control propellant

9440 tons total - resulting in an "orbit burden factor" (OBF) of 1.70

The LeRC is now reviewing these data and may subsequently suggest modifications to the ion thrusters' design, performance, and efficiency.



Payload, tons	36 (internal orbiter)
Payload, passengers	50 to 100
Orbiter, inert, tons	85
External tank, inert, tons	33
External tank, propellant, tons	714
Liquid rocket booster, inert, tons	144
Liquid rocket booster, propellant, tons	1531
Gross lift-off weight, tons	2600
Number of engines	4

Figure VI-4.- Personnel launch vehicle (PLV).

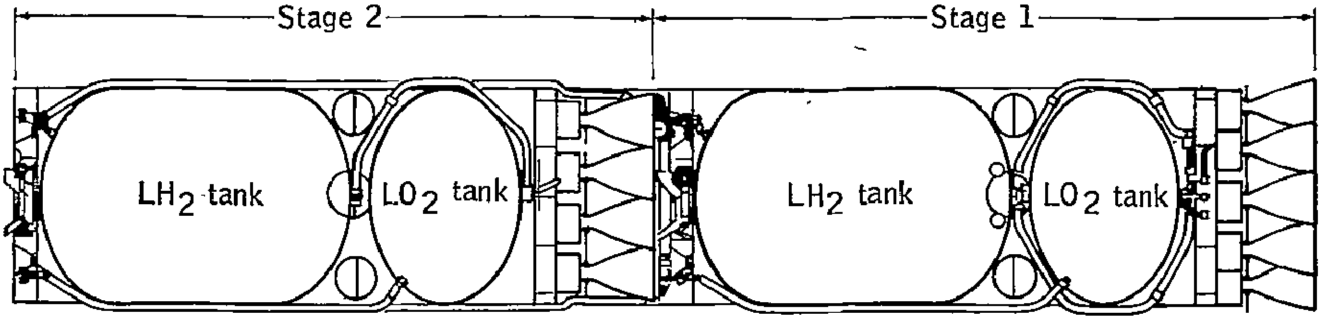
Another promising electric thruster is the MPD arc jet, also utilizing argon as propellant. Its primary attraction is a potential increase in thrust density by a factor of 500 to 1000 over that of the ion engine, to a thrust level of 150 N for a 50-cm-diameter aperture. This increase may permit the needed thrust to be produced with far fewer engines and less structural and electrical penalties to the SPS module for thruster installation. Princeton University (Dean Robert Jahn and Dr. Kenn Clark) is now characterizing a flight MPD engine for JSC for future comparison with the ion engine. The data base content for the MPD in the U.S. is sparse; hence, there is a need for accelerated technology development testing to confirm the MPD arc jet as an attractive candidate.

Further mission analysis is in progress in an attempt to reduce the need for O_2/H_2 attitude control during module occultation at lower altitudes of the transfer. If successful, this new mission approach may lower transportation costs. Finally, in work to date, it has been presumed that the electric thrusters and power-conditioning equipment are expended at GEO. In fact, a large portion of the thruster system may serve the related stationkeeping and attitude control needs of the operational SPS, once built. Should analyses indicate that portions of the thruster assemblage are not needed for SPS operation, it may prove cost effective to return the equipment from GEO by chemical (O_2/H_2) OTV for refurbishment and subsequent reuse.

For construction in geosynchronous orbit, the provision of independent power for transit propulsion by the $COTV_G$ will be required. The source of this power may be conversion of solar energy by an element of the COTV, a nuclear reactor power source, or stored chemical energy. Although radiation-tolerant solar arrays, nuclear reactors, and beamed energy systems may be competitive for this role, a lack of reliable characterization data has led to the conservative choice of stored chemical energy - in the form of liquid-hydrogen and liquid-oxygen propellant. The selected reference $COTV_G$ configuration, common stage, is shown in figure VI-5.

E. Personnel Orbital Transfer Vehicle

The POTV will be utilized to transport all personnel from LEO to GEO and back to LEO and to transport high-priority cargo to GEO. The short trip time (less than 1 day) and small payload requirement of the POTV preclude commonality with the high-specific-impulse, low-thrust cargo OTV systems being considered. The POTV is considered as a special-purpose device optimized for personnel transfer between LEO and GEO. Last year, use of the high-thrust-chemical $COTV_G$ was considered for transporting personnel. This option is no longer favored because of the necessity to man-rate the $COTV_G$, the complexity of combining cargo and personnel or transporting large numbers of personnel to obtain sufficient payload, and, more importantly, the probable requirement for a specialized POTV in the early stages of the program prior to the need for the COTV.



Common stage LO_2/LH_2
Life: 50 missions
Payload: 250 tons
≈ $2.6 x 10^6/flight

Length: 51.4 m
Diameter: 8.4 m
Total weight: 610 tons
Propellant weight: 564 tons

Figure VI-5.- Cargo orbital transfer vehicle ($COTV_G$) characteristics.

The POTV LEO-to-GEO mission is assumed to be initiated at the LEO orbit transfer operation base. Modular OTV elements are docked, and propellant load on the synchronous transfer ellipse with a trip time of 8 to 9 hours. At apogee, the circularization maneuver is performed and rendezvous with the GEO SPS construction base is accomplished. GEO orbital stay for a typical mission is between 2 and 7 days. Orbital stay time can be extended for GEO refueling applications. Return to the LEO base is all-propulsive.

For the purpose of this study, the conservative choice was made to employ conventional chemical propulsion, with all-propulsive return of the vehicle and crew to LEO. Single-stage, 1-1/2 stage (outbound propellant tanks expended), and common-stage configurations are all candidates for this mission. Additionally, for those cases in which economic cargo transportation is available, significant advantages accrue to the POTV by storing propellant in GEO (having previously been delivered by the cargo OTV) for the return journey.

A crew module concept layout is shown in figure VI-6. During the operational program phase, the crew module will be used as the manned control compartment for the POTV, now transporting the crew rotation passenger module, which is shown in figure VI-7. High-priority cargo may be carried as POTV payload instead of, or in addition to, the crew rotation passenger module.

Results of a parametric sizing study indicate that, although the 1-1/2 stage candidate required less LEO start-burn mass, the common-stage (two identical stages) candidate may provide more versatility to the transportation fleet with its capabilities for operation as a single stage (each stage individually), for total reusability to LEO-GEO sortie missions operations, and for GEO refueling of the second stage for return to LEO.

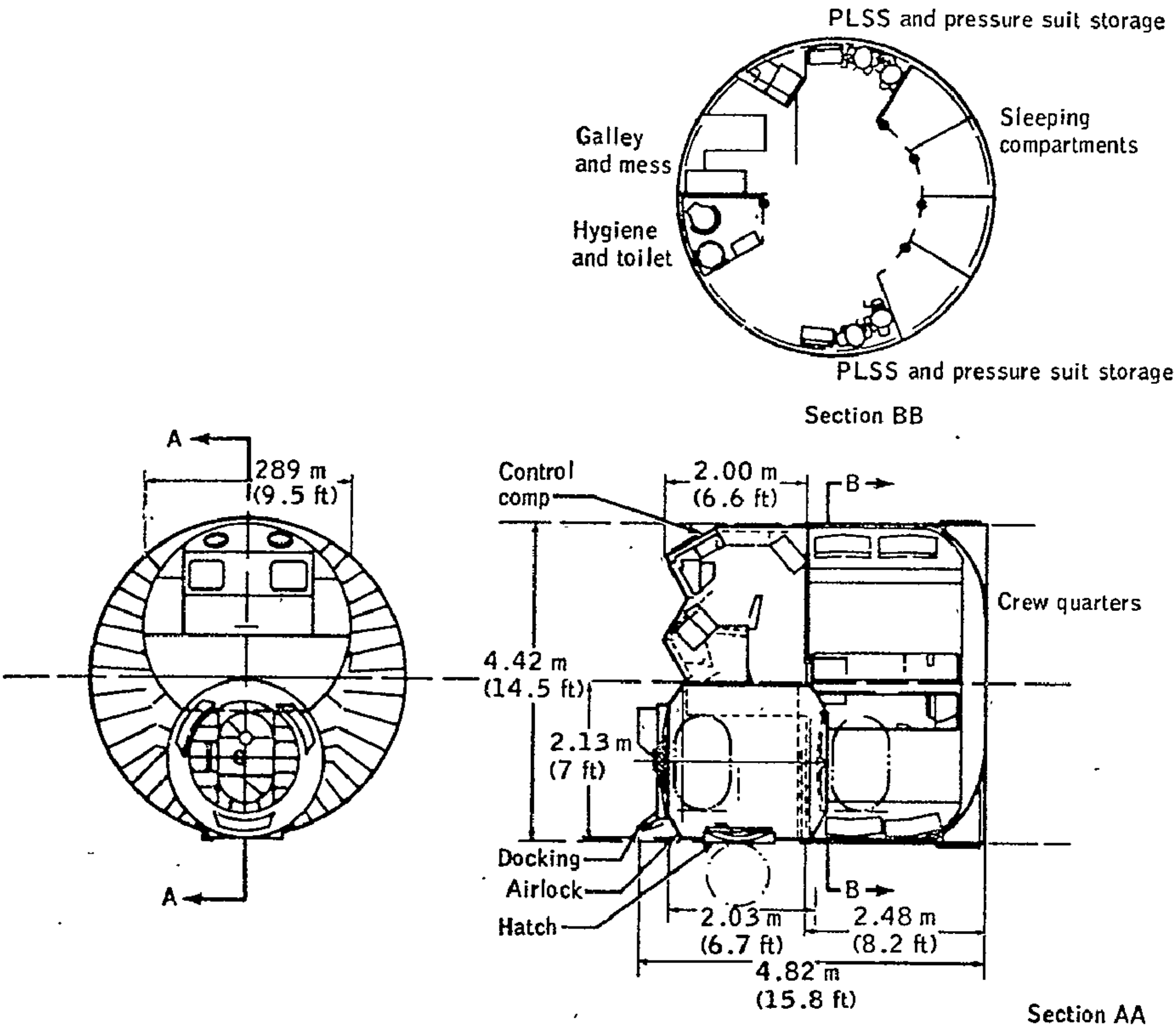


Figure VI-6.- Crew module concept.

In addition, the individual stages are compatible with the Shuttle payload bay. The sizing mission for the POTV is assumed to be the GEO manned sortie mission (precursor to the SPS), with total reusability and turnaround at LEO.

The common-stage concept consists of two nearly identical stages used in series to provide the required mission delta velocity. The first of these stages is used to provide approximately 85 percent of the delta velocity required for acquiring the elliptical geosynchronous transfer orbit on a crew rotation flight. The second stage provides the remainder of the transfer delta velocity, as well as that required for circularization at the destination orbit and both of the return maneuvers. Following

No. of passengers	Dimension "A" length, m	Gross weight, tons
50	8.88	13.44
75	11.66	19.60
100	14.44	30.24

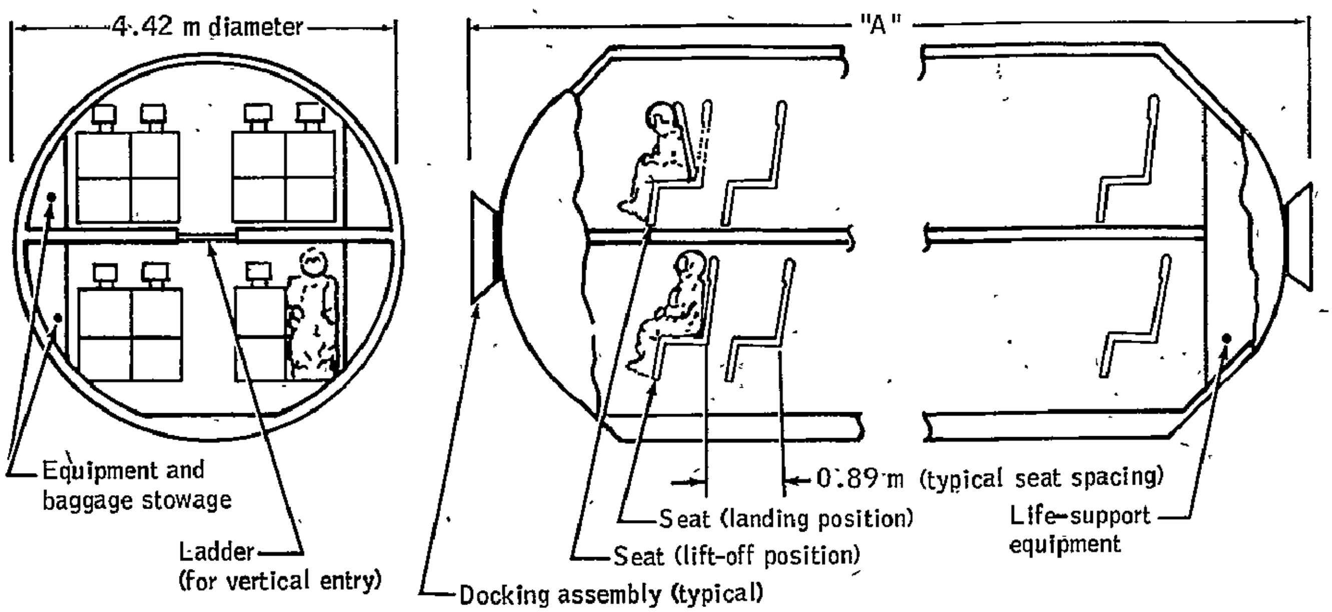


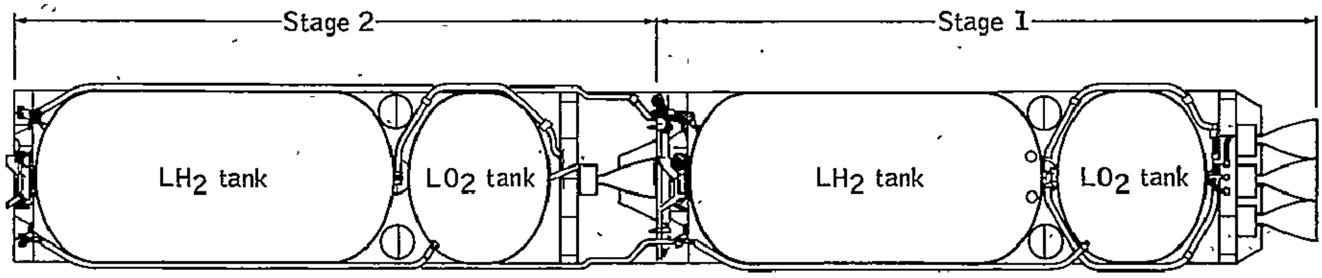
Figure VI-7.- Crew rotation passenger module.

separation from stage 2, stage 1 is retrograded into the Earth's-circular departure orbit. Splitting the delta velocity in the aforementioned manner results in the stages having identical propellant capacities. Subsystems design approaches are also common between the stages, including the size of the main engine.

A representative POTV configuration and characteristics are shown in figure VI-8. The dimensions of the stages are Shuttle compatible but, because of their propellant requirements, will require on-orbit refueling. A 75-man crew rotation module plus over 20 metric tons of priority cargo can be carried to GEO in the operating mode wherein stage 2 is refueled at GEO.

F. Summary of Projected Transportation System Characteristics

The results of studies of the various transportation elements necessary to support the SPS program have been presented in the previous sections. In this section, the results are expressed in terms of minimum, nominal, and maximum estimates of characteristics for each transportation element (HLLV, PLV, $COTV_G$, $COTV_L$, $POTV_G$, $POTV_L$). The MINIMUM estimates are the most optimistic combination of characteristics, whereas the MAXIMUM estimates are the most pessimistic, with the NOMINAL estimate



Common stage LO_2/LH_2
Life: 50 missions
Payload: 75 passengers + 20 tons (up)
75 passengers (down)
(2nd stage GEO refuel)
≈\$3 x 10^6/flight

Length: 33.28 m
Diameter: 4.42 m
Total weight: 129 tons
Propellant weight: 108 tons
Number of engines at 66 720 N each:
Stage 1 : 4 engines
Stage 2 : 2 engines

Figure VI-8.- Personnel orbital transfer vehicle (POTV) characteristics.

lying between these extremes. These vehicle estimates are presented in tables VI-3 to VI-6.

For the SPS space transportation scenario, all OTV's are based at LEO for fueling and flight vehicle turnaround activities. It was assumed that all OTV propellants are delivered by HLLV to a LEO depot "tank farm" or staging depot for propellant storage before OTV fueling. There will be propellant losses associated with this storage/transfer activity in terms of daily boiloff, transfer residuals, and chilldown losses. For reference, in the FY 1976 study, preflight propellant losses were estimated conservatively at 30 percent and 50 percent for LEO fueling and GEO fueling, respectively. For the FY 1977 study, a better understanding of OTV fueling systems and mission sequence has enabled a substantial reduction in propellant loss estimates, as well as separate estimates for each fluid. The $COTV_L$ and $POTV_L$ systems and operations used for the SPS LEO assembly option have been analyzed to have a propellant loss percentage of 6.9 percent. Similarly, the $COTV_G$ and $POTV_G$ systems and operations result in a loss percentage of 6.1 percent. The special case of the POTV second-stage-return propellant was also treated, and a propellant mass loss percentage of 10.8 percent and 19.0 percent was determined for the GEO propellant handling mode for the $POTV_G$ and $POTV_L$, respectively. These new data were input to the scenario program to account for the OTV preflight and flight ($COTV_L$ only) propellant losses and consequent additional launch costs. The reduction in the FY 1976 versus FY 1977 propellant loss estimates resulted in an overall reduction in its percentage effect on the total SPS program transportation cost from 5 percent to 1 percent for LEO construction and from 15 percent to 4 percent for GEO construction.

TABLE VI-3.- HLLV RANGE OF PROJECTED ESTIMATES

Characteristics	Minimum	Nominal	Maximum
Payload/flight, metric tons	445	424	382
Flight cost:			
$ million/flight	7	9	14
$/kg	16	21	37
Flight turnaround, days	5	6	7

TABLE VI-4.- PLV RANGE OF PROJECTED ESTIMATES

Characteristics	Minimum	Nominal	Maximum
Passengers/flight	100	75	50
Flight cost, $ million/flight	10.2	13.5	16.2
Flight turnaround, days	9	11	13

The nominal estimates of tables VI-3 to VI-6 were used to derive the cost of transportation for a nominal weight SPS with the two configuration/construction location options. These results are presented in table VI-7 and indicate the expected reduced costs of constructing the system in LEO, with utilization of energy from the system to provide power for orbital transfer. The calculations also indicate the small percentage (less than 10 percent) of costs involved in manned support.

The FY 1977 results in table VI-7 may be compared to the FY 1976 results in table VI-8. The total specific transportation costs, expressed in dollars per kilogram, for an SPS emplaced at GEO have decreased from 165 to 93 (truss constructed at GEO) and from 108 to 52 (truss constructed at LEO). The substantial decrease in the total specific transportation costs from the FY 1976 to FY 1977 estimate is apparent in the HLLV and COTV components. For the HLLV, dollars per kilogram to LEO decreased from $33/kg for the FY 1976 nominal estimate to $21/kg for FY 1977 because of a better understanding of the flight operations in addition to reusing the

TABLE VI-5.- COTV RANGE OF PROJECTED ESTIMATES

Characteristics	$COTV_G$			$COTV_L$		
	Min.	Nom.	Max.	Min.	Nom.	Max.
Payload/flight, metric tons	300	250	200	2926	5753	8828
Total inert weight, metric tons	36	36	36	422	829	1413
Propellant/flight, metric tons	574	574	574	779	1632	3393
Flight cost:						
$ million/flight	1.7	2.6	3.9	41	88	146
$/kg	6	10	20	14	15	17
Flight turnaround, days	5	6	7	N/A	N/A	N/A
Mission life, no. of missions	100	50	25	1	1	1

TABLE VI-6.- POTV RANGE OF PROJECTED ESTIMATES

Characteristics	$POTV_G$			$POTV_L$		
	Min.	Nom.	Max.	Min.	Nom.	Max.
Passengers/flight, no.	100	75	50	100	75	50
Inert weight, metric tons	21	21	21	21	21	21
Propellant up, metric tons	108	108	108	108	108	108
Propellant down, metric tons	54	54	54	54	54	54
Flight cost, $ million/flight	2.4	3.0	3.8	2.4	3.0	3.8
Flight turnaround, days	5	6	7	5	6	7
Mission life, missions	100	50	25	100	50	25

payload shroud. The COTV estimates decreased from FY 1976 with the removal of the DDT&E component in the unit cost and better understanding of the flight systems and operations. These reductions, expressed in dollars per kilogram to GEO, are $40/kg to $10/kg ($COTV_G$) and $30/kg to $15/kg ($COTV_L$). In addition, nominal SPS satellite mass estimates decreased 13 percent from FY 1976 to FY 1977.

TABLE VI-7.- RELATIVE TRANSPORTATION COSTS FOR SPS CONSTRUCTION ONLY, FY 1977[a]

Transportation vehicle	Configuration and construction location			
	Truss GEO		Truss LEO	
	$/kWe bus	$/kg SPS	$/kWe bus	$/kg SPS
HLLV ($21/kg to LEO)	607	78	297	32
PLV	30	3	38	4
COTV	86	11	143	15
POTV	6	1	3	1
Total	729	93	481	52

[a]For SPS's emplaced at nominal cost and weight.

TABLE VI-8.- RELATIVE TRANSPORTATION COSTS FOR SPS CONSTRUCTION ONLY, FY 1976[a]

Transportation vehicle	Configuration and construction location			
	Truss GEO		Truss LEO	
	$/kWe bus	$/kg SPS	$/kWe bus	$/kg SPS
HLLV ($33/kg to LEO)	1076	120	661	73
PLV	30	3	37	4
COTV	373	41	273	30
POTV	7	1	6	1
Total	1486	165	977	108

[a]For SPS's emplaced at nominal cost and weight.

As in the FY 1976 results, the HLLV dominates the SPS transportation cost and operations picture. The accuracy of the HLLV cost-per-flight estimation is critical; thus, the complexities of operating the large fleet of HLLV in multiple daily flights need thorough study to evolve realistic operations/manpower cost estimates for each HLLV flight. Manpower costs are now estimated to comprise one-third to one-half of the cost per flight, representing approximately 35 percent to 26 percent of the total SPS transportation costs for GEO and LEO construction, respectively.

For the LEO construction case, the cost advantages of the $COTV_L$, with its lower propellant requirements, are obvious in comparison to the conventional $COTV_G$. With consequent lower HLLV flights required, the option of self-powered transfer by $COTV_L$ is one-third less costly than the option of chemical propulsion high-thrust transfer for SPS GEO construction. However, in terms of technical risk, the $COTV_G$ vehicle and operations are better understood than the $COTV_L$ at this time.

VII. ENVIRONMENTAL FACTORS

A. Microwave Transmission and Reception

The transmission of a very powerful microwave beam through the ionosphere and its reception/detection on the ground will produce several effects, all the way from "immeasurable" to possibly quite significant. In the last year, a number of these effects have been examined, and the magnitude of the perturbations produced has been estimated. Also, areas needing additional work have been identified and plans made for studies in fiscal year 1978.

The radio frequency cumulative power density in the far side lobes of 100 10-GW power stations has been ascertained to be very low, about 10^{-4} mW/cm^2. This is two orders of magnitude below the U.S.S.R. radiation limit and five orders below current U.S. limits.

Losses of microwave power at the rectenna site due to ground absorption and diode detection are estimated to be about 7.5 W/m^2. This should be compared with a 24-hour average solar heat absorption of 230 W/m^2. A change in the Earth albedo of only 2 percent can therefore outweigh the rectenna site waste heat losses. If the albedo increases by more than 2 percent, the local site would reflect back more energy to space than produced by microwave losses.

It is also useful to compare the rectenna heat generation with the thermal effects of a "bedroom community" of approximately 150 000 people. Both may cover a land area of some 100 km^2 and release about 750 MW of thermal power near the ground, yet, major tropospheric or weather alterations have not been found to be associated with communities of this size, either singly or collectively, among the hundreds of such cities scattered across the United States. A group of expert consultants have concluded that for over 200 rectennas there would be no detectable effect on global weather (where detectable implies within the constraints of our ability to monitor such a small thermal forcing (function) on a global scale).

Passage of the microwave beam through the ionosphere may produce both direct and indirect effects of concern. It will directly produce heating of the plasma and an increase in the electron temperature at altitudes from as low as 75 km to above 400 km. It may produce electron concentration irregularities, which would lead to an indirect effect on terrestrial communications channels.

The electron heating effects can be calculated from standard equations for "ohmic losses" suffered by electromagnetic wave propagation through an ionized medium. When these losses are included in rather sophisticated models of the ionosphere, the new equilibrium electron temperatures may be found. These calcuations show increases in excess of 1000 K below 100 km (where electron densities are low) and about 600 K at 300 km, near the maximum F-region electron concentration. These very substantial increases will require further investigation.

Also of concern is a theoretical prediction of large-scale irregularities in the ionosphere generated by "thermal self-focusing." A theoretical threshold for this effect exists at about 23 mW/cm^2 for a wave frequency of 2.45 GHz. At power densities greater than this threshold, large-scale irregularities may be formed, aligned with the local magnetic field. The microwave beam would tend to be focused by refraction into areas of lowest electron concentration. The increased power density leads to larger ohmic losses and higher electron temperatures, causing further expansion of the plasma and even lower electron concentrations.

Thermal self-focusing has not yet been verified experimentally, although another type of interaction (parametric instability), observed when the wave frequency is near the local plasma frequency, is well known to cause strong ionospheric irregularities. Both kinds of interactions were investigated during tests run in June 1977, at the Arecibo Observatory. Transmitters at high frequency (4 to 11 MHz), at 430 MHz, and at 2300 MHz were used. Although power densities at ionospheric altitudes are still at least an order of magnitude below those required by theory for thermal self-focusing instabilities at S-band, it was a useful test. The power density of the 430-MHz test at a height of 200 kilometers was 0.6 mW/cm^2, which is 1/12 of the equivalent SPS level in a 1-kilometer heated cross-sectional area; the corresponding density for the 2300-MHz S-band test was 1.1 mW/cm^2, which is 1/20 of the equivalent SPS level in a 200-meter heated cross-sectional area. No nonlinear effects were observed by the diagnostic radar at Guadeloupe for any of the heating frequencies. These negative results were as anticipated. Cost estimates are also being prepared for a higher power test to reach the predicted threshold levels.

An investigation of the indirect effects of the ionospheric interactions has begun. If irregularities should be created in the ionosphere, it is possible that a variety of radio signals that transit the ionosphere might be adversely affected. They may be conveniently grouped into communications, radar, and navigation (COMMRAN) systems. Many of the potentially affected systems have been identified, but most of the necessary studies to determine the degree to which they may be affected by ionospheric irregularities have not yet started.

Irregularities and gradients in the electron density distribution in the ionosphere can also affect the phase of the "pilot beam" transmitted from ground to the SPS and thereby affect the pointing control of the microwave power beam. These effects need to be evaluated, and work is planned in this area for next year.

Several comprehensive reviews of the effects of microwave radiation on humans have been summarized. General agreement exists that exposures for a sufficient time to microwaves at power densities greater than 100 mW/cm^2 can cause irreversible pathological effects. No uniformity of views exists on what power density is harmless, especially when comparing the views of the Eastern European countries with those of the United States and Western European countries. Most U.S. researchers and all U.S. standards-setting agencies currently agree that continuous exposure at 10 mW/cm^2 does not produce irreversible pathological thermal effects.

The 10-mW/cm^2 limit is based upon simple thermal considerations. The human body can transfer at least 10 mW/cm^2 of heat to the external environment, under normal circumstances, without a continuous rise in body temperature. Because much of the microwave energy is reflected or not absorbed by the human body, the use of the 10-mW/cm^2 limit provides a built-in margin of safety from thermal hazards.

Some research reports, especially from the Eastern European countries, suggest that nonthermal effects involving the central nervous system can result from exposure to microwaves at power densities less than 10 mW/cm^2. Most of these reported effects are subjective (i.e., headache, fatigue, irritability, etc.) and occur only in a small portion of the persons exposed to the same low-power densities. Moreover, the effects are usually reversible and do not represent pathological changes. Nonetheless, such effects could lead to performance decrements in a susceptible portion of an exposed population. The Eastern European "standards" (10^{-6} W/cm^2 for continuous exposure) are based upon these reported central nervous system effects. Actually, the "standards" are just guidelines, which are exceeded in practice. The guidelines reflect the Russian industrial hygiene philosophy that the limit should be set at the point that is expected to prevent any deviation from normal.

Should a more general agreement be obtained on performance decrement associated with microwave power densities lower than 10 mW/cm^2 the U.S. safety limit may have to be lowered. Because these low power density effects appear to be related to the frequency of the microwave radiation and to whether the beam is continuous wave, pulsed, or amplitude-modulated, any potential new lower limits will likely be more specific as to these radiation characteristics.

B. In-Space Operations

A starting point for any environmental study should be a thorough description and understanding of the unperturbed or natural environment. The natural space environment, and especially that of geosynchronous orbit, provides extra difficulties, because its dynamic activity is quite large. In geosynchronous orbit, the ambient, thermal electron concentration may change by more than an order of magnitude, depending on the plasmasphere location. The energetic particle population and energy distribution may change by several orders of magnitude, depending on the solar wind conditions and the occurrences of flares and magnetic storms.

Preliminary documents have been prepared describing the particle and field distributions at GEO, and statistical summaries based on published satellite observations have been generated. Physical models have also been prepared.

From measurements of the energetic particle fluxes, levels of safety of manned operations can be established. Three principal contributors need to be considered: galactic cosmic rays, energetic particles trapped in the geomagnetic field, and solar proton events. Galactic cosmic rays are so energetic that shielding becomes impractical; however, their flux is suffiently low that average dose rates of only about 30 mrad/day are expected. In LEO, the trapped radiation does not produce an excessive

dose rate with modest shielding, such as was used in Skylab with a circular orbit of 435-kilometer altitude and 50° inclination. In transit to GEO, the dose rate becomes much larger, with contributions from both energetic protons and electrons in the Van Allen belts. At GEO, with an aluminum shielding of 3 g/cm^2, a dose rate of about 0.3 rad/day is expected, mostly from electron bremsstrahlung. Dose rate climbs rapidly for shielding less than 2 g/cm^2 as might be encountered during EVA.

Solar proton events plainly pose a health hazard to operations in GEO as they did on Apollo lunar missions. It has been found that these high-energy protons do have direct access to the GEO altitudes. Some extra shielding is obviously required to reduce the probability of receiving an excessive dose. Calculations show that the protection afforded by 10 g/cm^2 would have been adequate to reduce the received dose in 98 percent of the solar proton events in two full solar cycles (numbers 19 and 20) to a level below the allowable quarterly dose to blood-forming organs.

A novel way has been suggested to reduce the radiation effects of energetic electrons trapped in the geomagnetic field. These particles produce radiation effects that not only are significant to humans but also are very important to the useful lifetimes of solar cells and reflectors. The proposal is to launch very low-frequency radio waves from spacecraft within the ionosphere or magnetosphere; the radio waves are then guided by the Earth magnetic field. The waves will interact with a portion of the energetic electron population and cause their "pitch angles" (angle between their velocity vector and the Earth magnetic field) to be reduced. When reduced sufficiently, the electrons will penetrate to lower "mirror" altitudes and be "precipitated" by collisions with atmospheric molecules. In this manner, the total population of energetic particles may be reduced substantially, with correspondingly lower radiation damage. Theoretical work is currently in progress, with a possible space demonstration required in later years.

An additional hazard is associated with collisions with space debris. Uncertainty in predicting collision frequency comes principally from two sources: (1) the actual number of orbiting objects below the level of NORAD radar detectability down to the size of about 1 millimeter and (2) the consequence of a collision, especially the damage produced and the number of ejected "daughter" products. The present uncertainty in collision frequency for the year 2000 is about 4 orders of magnitude. This uncertainty implies the need to be very careful to minimize the rate at which new objects are added to orbit (especially small, numerous objects) and a possible need for removing debris ("space cleanup") at some later date. To reduce the uncertainty and to identify preferred design requirements, the following tasks are required: (1) construct or improve time-dependent space-debris models, (2) improve the data base for smaller objects, (3) design structures to minimize collision damage, (4) identify crew-safety design constraints, and (5) consider trade-offs among constraints on the generation of additional space debris and requirements for debris removal.

VIII. MANUFACTURING, NATURAL RESOURCES, TRANSPORTATION, AND ENERGY CONSIDERATIONS

In the past year, work on manufacturing, natural resources, transportation, and energy considerations has been performed primarily to examine the following areas in more detail.

A. Aluminum requirements, primarily for the rectenna

B. Gallium supply, for potential replacement of silicon solar cells with gallium arsenide solar cells

C. Surface transportation of fuel to a launch site

D. Energy payback for SPS weight ranges

Finally, the energy payback was discussed, considering its relationship to electrical powerplants run with fossil fuels and with the nondepletable-fueled SPS.

A. Aluminum Requirements

During the past year, the structural design of the rectenna has been studied. One reason for conducting the study was to reexamine the previously projected quantity of aluminum required for structural integrity and to determine if this quantity, resulting in a 7-percent increase in the projected annual demand for aluminum in the United States in the year 2000, could be reduced. This study is reported in section IV.D.3. of Volume II of this report. In the designs examined in the study, the projected quantity of aluminum serves the dual function of power transmission and as a structural support member in an otherwise all steel structure. This aluminum requirement is a major portion of the aluminum demand for SPS program; however, because of the change to a basically steel support structure, the previously predicted 7 percent increase in the projected annual U.S. aluminum demand for the year 2000 would be reduced to 2 percent based on the construction of four 5-GW rectennas in that year.

B. Gallium Supply

Although gallium arsenide solar cell technology is in early stages of development, several potential advantages over silicon cells have been identified. These advantages include higher electrical conversion efficiencies, shorter light-absorption paths (leading to thinner cells), and lower potential radiation damage. These advantages all tend toward smaller, lighter solar cell arrays. The single major known disadvantage of gallium arsenide cells is the possible lack of adequate gallium for cell production.

A study was conducted which addressed the amount of gallium required for the SPS program and the availability of gallium from the two major sources, aluminum ore and coal fly ash. The amount of gallium needed for

the SPS program and the amount available are highly dependent upon the following factors.

1. Satellite output power

2. Solar cell efficiency

3. Overall satellite system efficiency

4. Supply source

   a. Aluminum ore mined

   b. Gallium concentration in the ore

   c. Coal fly ash produced

   d. Gallium concentration in the fly ash

5. Projections of availability from the supply sources

6. Collection efficiencies for the preceding sources

7. Extraction efficiency for the various sources

Several significant conclusions can be drawn from the study.

1. Widely varying amounts of available gallium can be projected, based on differences in supply, extraction efficiency, and collection efficiency.

2. If emphasis is placed on gallium recovery, then it appears that in excess of 100 000 Mt of the metal can be produced from U.S. coal/fly ash and U.S.-required aluminum ore from friendly countries by 2025.

3. Gallium arsenide solar cells must approach 5 to 6 micrometers in thickness, to allow for production of 112 satellites in the 10-GW range with the availability of the 100 000 Mt of gallium.

C. Surface Transportation Requirements

1. Continental United States

A preliminary study was conducted to examine the Earth transportation requirements, assuming a 1500 mile transportation distance. The study examined payload and fuel transportation requirements to support a scenario B 112-SPS implementation rate. Results of this study indicate that payload transportation requirements are small, being about 0.06 percent of the 1583 x 10^6 Mt of 1974 U.S. waterborne commerce in the busiest year; however, the fuel transportation may become significant. After this study, a mine-mouth gas-transmission system for booster fuel was examined and is reported in volume II, chapter VI.

For the use of RP-1 for first-stage fuel and hydrogen for the second stage, fuel-delivery requirements are as depicted in table VIII-I.

TABLE VIII-1.- FUEL DELIVERY REQUIREMENTS

Fuel		7 SPS plus O&M/yr
RP-1, Mt	1.17×10^6	9.59×10^6
H_2, Mt	0.31×10^6	2.51×10^6
Coal gasification		
Coal, Mt	5.55×10^6	45.1×10^6
Water, gal	6457×10^6	52560×10^6

Assuming hydrogen is to be derived from coal, 5.55×10^6 Mt of coal would be required for one SPS. An alternate approach utilizing electricity obtained from a rectenna for electrolysis of water would alleviate this large coal-transportation requirement.

The cost of hydrogen using electrolysis and a cost of 59 mills/kWh for electricity from an SPS is $2.21 per pound.

2. Equatorial Launch Considerations

Two major factors must be considered in launch-site location: fuel requirements and operational flexibility. A 15-percent savings of propellants is achieved between an equatorial site and a launch site at the KSC latitude, because the plane change by the COTV is eliminated at the Equator. From this savings must be subtracted the fuel requirements of surface transportation to the equatorial site. The surface-transportation fuel requirements cannot be defined completely at this time, because the materials to construct and support the launch facility may either be shipped from the CONUS or be acquired locally. In the analysis, the trade-off seemed slightly in favor of equatorial sites. Using larger ships, with their more efficient cargo/fuel ratios, would tend to indicate a net fuel savings using an equatorial site.

Operationally, the trade-off may be heavily in favor of an equatorial launch site, especially in scenarios requiring high daily launch rates. Launch windows to a 35° orbit from KSC occur approximately every 14 hours, or 1.7 times per day. From the equatorial sites, windows are available every 90 minutes, or 16 times per day. Thus, factors other than surface transportation may govern the launch site location.

D. System Energy Balance

The JSC report (JSC-11568) last year reported a one-design-point number of 0.83 year payback. This point number has been expanded to include the energy-payback variations for different SPS masses, including solar cells, ballistic and winged boosters with their fuel and oxidizers. This variation is shown in figure VIII-1 in which the energy payback ranges from 0.83 to 1.6 years. In addition, in this figure, one can see the energy-payback difference between an all-aluminum rectenna structure used in last year's report and a structure made of steel as discussed in section IV.D.3.

In making energy-payback calculations of conventional plants, historically only the energy required in the manufacturing and construction of the generating station is considered and the lifetime fuel required in the operations and maintenance are ignored. The primary advantage of

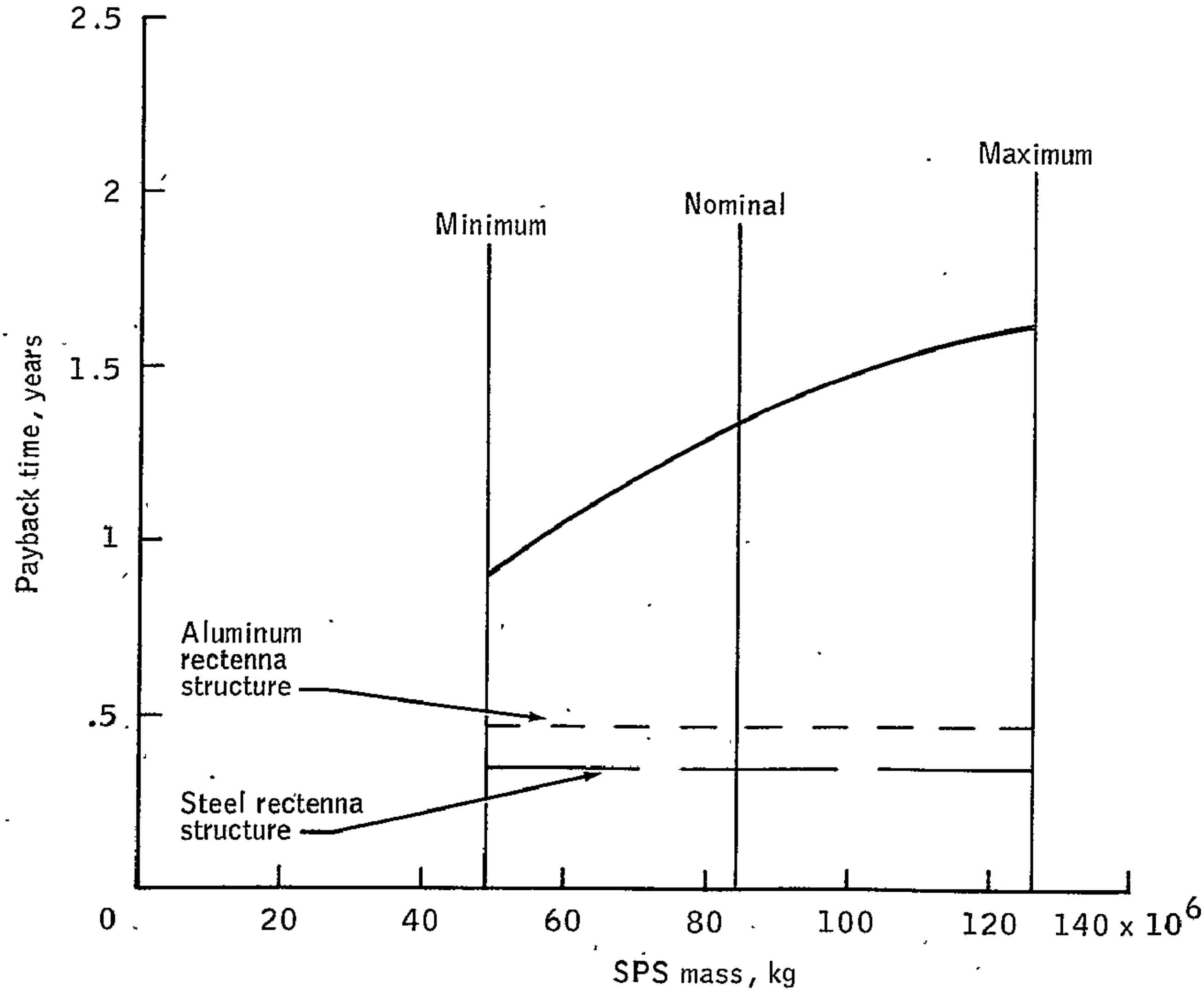


Figure VIII-1.- Payback time in years versus SPS mass chemical transplant.

solar cycles is that the fuel requirement for operation is zero. The more meaningful comparison between conventional and solar sources is the total amount of depletable fuels used to construct, operate, and maintain them over their lifetimes. Implementation of scenario B, as compared to supplying the electrical power conventionally, results in a savings equivalent to 43 percent of proven U.S. crude reserves in 1975. By continuing to operate scenario B (112 satellites) over a period of 30 years, the equivalent of 136 percent of 1977 proven crude reserves can be saved.

In a comparison of space solar power with ground solar power, cumulative energy in and out goes positive in the fifth year for space power in scenario B, whereas 19 years are required to break even with ground solar power. An improvement in both cases is shown if a constant implementation rate is selected, rather than the continuously increasing rate of scenario B. The break-even times on cumulative energy are then 4 years and 15 years, respectively.

IX. PROGRAM DEVELOPMENT

A number of planning activities have occurred in the past year which include the joint NASA/ERDA plan, a JSC technology advancement plan, and related JSC studies. The following briefly describes these plans and studies.

A. NASA/ERDA SPS Concept Development and Evaluation Program Plan 1977-1980

A joint plan has been developed between NASA and ERDA. The basic objectives of this plan are to develop sufficient understanding of the technical requirements, economics, practicability, and social and environmental acceptability of the satellite power system concept to enable a preliminary program continuation decision to be made in CY 1979 and a final decision to be made in CY 1980 to either continue with the program at a level of effort to be determined or to phase it out. The basic elements of this plan are studies relating to (1) system definition, (2) space-related technology, (3) environmental factors, (4) effect and benefits, and (5) comparative evaluations. The major milestones, schedule and funding levels of these activities are shown in table IX-1.

TABLE IX-1.- NASA-ERDA PROGRAM DEFINITION PLAN (CONCEPT EVALUATION)

Task description	FY 1977	FY 1978	FY 1979	FY 1980	
	System concepts defined (a) ◆	Preferred concepts selected (a) ◆	Preliminary program continuation (a) ◆	Final program continuation decision (a) ◆	Total funding (a)
Systems definition studies (2)	$1.8	$1.7	$1.3	$0.8	$5.6
Space-related technology	.7	1.8	1.2	.8	4.5
Environmental factors	.6	1.7	2.0	1.7	6.0
Effect and benefits	.2	.5	.5	.3	1.5
Comparative evaluations	.1	.4	.8	.6	1.9
Total by year	$3.4	$6.1	$5.8	$4.2	$19.5

[a]Millions of dollars.

B. Technology Advancement Plan

Previous SPS studies have produced a wide variety of configurational approaches, but have had at least one conclusion in common—although the concept appears feasible, substantial advances are necessary in many technical areas before an SPS program could be initiated with a reasonable degree of confidence. Within the area of technology advancement, in-house studies were made of (1) overall SPS technology requirements and (2) development flight activities.

1. Technology Advancement Requirements (1980-1987) - After the publication of last year's study results, a 3-month effort was initiated to establish (1) a comprehensive list of critical SPS technology areas and (2) a preliminary definition of an integrated technology advancement program necessary before the initiation of an SPS development program. The results of this effort have been documented as "Preliminary Assessment of Technology Advancement Requirements for Space Solar Power," March 1977 (JSC-12702), that can be consulted for more details.

For this study, "critical technology area" was defined as any technical problem that must be resolved prior to an SPS program implementation decision. The definition was intentionally broad and encompassed such questions as the following.

a. Feasibility of system and component design concepts

b. Component performance and efficiency

c. Component producibility in required quantities

d. Properties of materials

e. Understanding of natural phenomena

f. Verification of analyses

Development of the SPS itself was not included in this definition. Where the state of the art was such that a problem was reasonably assured of a solution during a normal development program, that problem was not considered a "critical technology area." However, the existence or anticipated existence of a solution to a problem did not rule out the inclusion in the program of other possible solutions offering significant potential improvements in weight, cost, etc.

The critical areas identified during this study are listed in table IX-2 by discipline. In several cases, a similar or identical problem was mentioned in connection with more than one discipline. These duplications or partial duplications are cross-referenced in the table. The listing within each discipline follows the order of the discussions in the detailed report and does not necessarily reflect any ranking in terms of importance, criticality, etc.

TABLE IX-2.- CRITICAL TECHNOLOGY AREAS[a]

A. Photovoltaic energy conversion

Solar cell bankets
- Thermal cycling
- Electron/proton and ultraviolet radiation effects
- Fabrication techniques

Solar concentrators (reflectors) (B, L)
- Radiation effects
- Micrometeoroid effects

Electrical and mechanical performance of very large arrays
High voltage/plasma interactions (L, M)

B. Thermal energy conversion

Radiator fabrication techniques (S)
Fluid-tight joints
Thin-film concentrator materials (A, L)
High-temperature heat exchanger materials
Superconducting generators and power cables
Leak detection and repair

C. Microwave system analysis

Ionosphere power density limits (D)
Microwave generator development (E)
Phase control techniques (G)
Slotted waveguide antenna designs, (F, L)
Rectenna development (H)

D. Microwave system

Transmission frequency
Ionosphere power density limits (C)
Heat dissipation from microwave generators and antenna (K)
Transmitting antenna construction and operation
Interfaces with transmitting antenna
Microwave system-level problems
Microwave effects on other areas

E. Microwave generation (C)

Efficiency
Reliability
Low noise
Low weight
Stability

---

[a]When an area is identified under more than one discipline, the other disciplines are cross-referenced in parentheses.

F. Antenna subarrays
Efficiency Power-level effects Manufacturing techniques (C, L)
G. Phase control (C)
Phase noise Interference rejection High-power phase stability Atmospheric phase perturbation Phase reference/control Phase control accuracy Fiber optics
H. Microwave reception (C)
Collection efficiency RF-dc conversion efficiency Factors influencing rectenna size Low-cost rectenna elements Sensitivity to beam power density and grid loads Pilot beam interfaces Maintenance
I. Distribution grid interface
(No critical technology areas)
J. Structural design
Solar collector structure/attitude control interactions (P) Antenna stiffness/pointing accuracy/attitude control interactions (O, P) Antenna subarray chassis/thermal control (K) Structural elements for space construction (S) Numerical characterization of SPS structural performance Similitude modeling for subscale testing Eclipse response (K)
K. Thermal control
Microwave generator thermal design (D) MPTS thermal control (D, J) Thermal design of rotary joint Thermal control of power distribution system Transient response of structure during eclispe (J)

TABLE IX-2.- Concluded

L. Materials

Availability of graphite for SPS construction
Graphite composite lifetime
Graphite composite cables
Tension cable lifetime
Application of vapor-deposited coatings in orbit
Solar concentrator film lifetime (A, B)
Thermal control surface lifetime
Joining techniques and properties (S)
Waveguide materials and fabrication techniques (C, F)
Electrostatic charging phenomena (A, M)

M. Power distribution

Thin-sheet conductors
Power bus insulation (A, L)
Power switching
System verification

N. Communications and instrumentation

(No critical technology areas)

O. Antenna pointing control (J)

(To be determined)

P. Stabilization and control (J)

(To be determined)

Q. Propulsion and reaction control

MPD arc-jet thruster
100-cm ion thruster

R. Rotary joint

Slip rings and brushes

S. Orbital construction

Automatic fabrication of elemental truss (J,L)
Assembly of elemental trusses into long truss (J)
Large space radiator construction (B)
Deployment and attachment of solar cell blankets
Deployment and attachment of planar concentrator membrane
Deployment and attachment of contoured concentrator membrane
Space installation of power distribution cables
Handling and berthing large modules
Integrity verification of space-fabricated structures
Assembly of jigs and fixtures for orbital construction
Fabrication of large pressure vessel in orbit

2. Flight Activities - The critical technology areas identified in the Technology Advancement Requirements Study can be categorized into requirements for ground tests, flight experiments (components and subsystems), and flight projects (integrated system flight tests requiring the interaction of two or more subsystems). This section presents descriptions of flight experiments and flight projects necessary in the development program for an SPS, and an analysis of the scale factors involved in deriving meaningful test requirements for testing the SPS structure in LEO.

Flight Experiments - Flight experiments as defined here includes the range of experiments that require going into space for SPS technology advancement. The simpler end of the range involves "suitcase" or package-size experiments which can be flown along with other payloads and accomplished by the crew in the space environment. An example is space welding which is critical to the automated fabrication process. Ultrasonic welding techniques developed on the ground would be applied with development equipment to candidate structural materials in space with the test articles returned to the ground for evaluation. Experiments of this type could begin in 1980 in the early operational period of the Shuttle.

A GEO environment/materials experiment would use an interim upper stage (IUS) to put a satellite in GEO to sense the SPS operational environmental parameters and telemeter them to the ground for verifying and improving analytical models. Environmental effects upon materials critical to the achievement of satellite design lifetime would be evaluated.

Subsystem experiments would be beyond the component level and involve significant pieces of or entire subsystems. A pertinent example of a subsystem experiment is a test of an entire scaled antenna subarray where microwave energy transmission could be made to sensors extended out on the Shuttle remote manipulator system (RMS). Operating in a space environment allows operational evaluation of power generator and antenna efficiencies, heat rejection, and transmission efficiency. Subsystem experiments would be required in the 1981-1984 period.

A Space Fabrication Experiment is the first flight test in the development of a new discipline — space construction. An automated fabrication module (or "beam builder"), a rudimentary construction facility (or "jig"), and a construction crew (extravehicular orbiter crew) would operate together in this experiment. A test structure would be constructed for evaluation of the beam builder, construction processes, and techniques, and would stay attached to the Orbiter during the load tests. This experiment could be flown in the 1982-1983 time period and represents close to the upper limit in scope of single-Shuttle flight experiments.

Using the automated construction process described in section V.C, the space fabrication experiment could be accomplished on one 7-day Shuttle flight with a crew of four. Figure IX-1 shows a typical test structure being constructed in the general shape of a ladder with automatically fabricated 1.5-m-wide truss members formed from flat reels of graphite fiber-reinforced thermoplastic. After deployment from a stowed launch

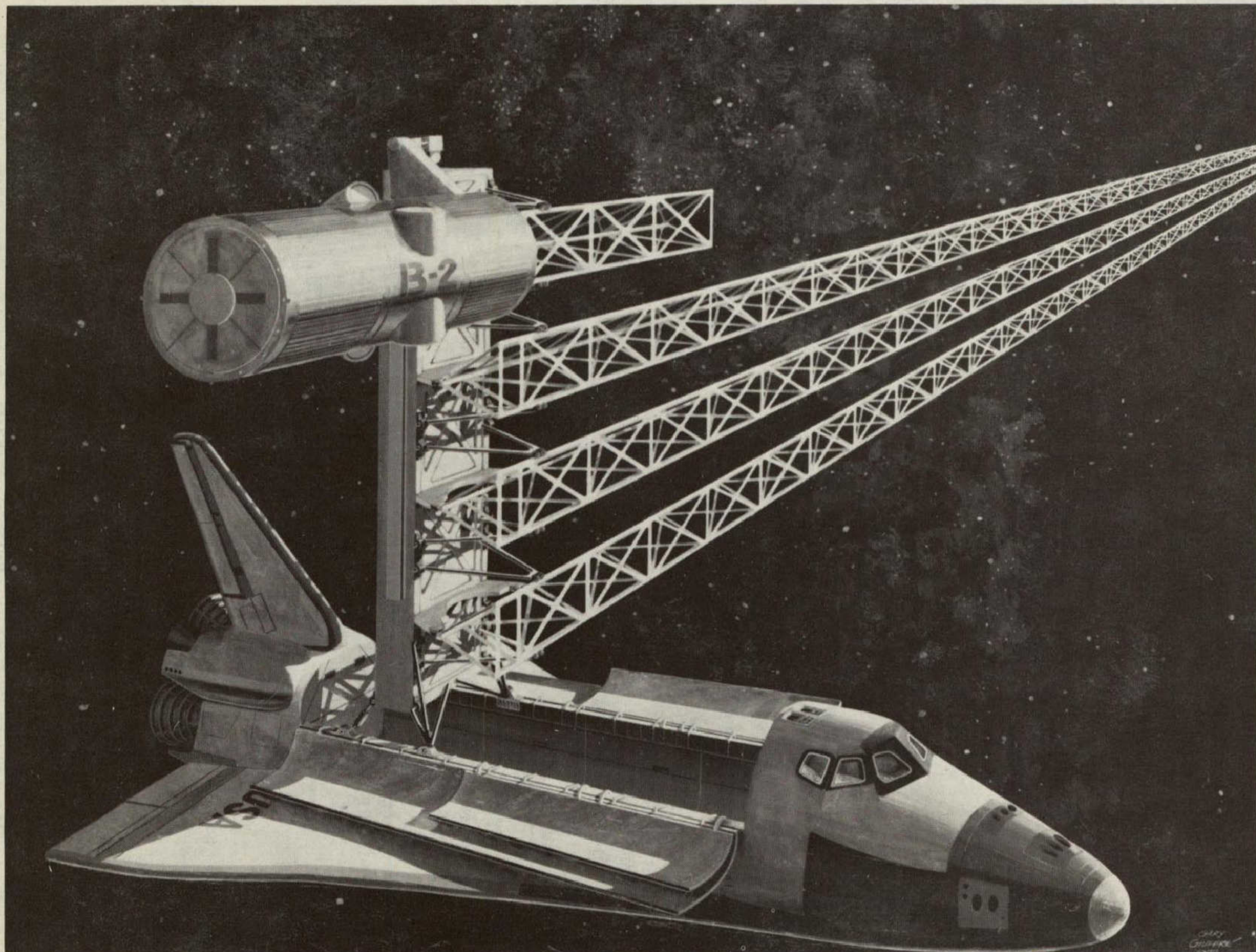


Figure IX-1.- Space fabrication experiment.

position, the automated fabrication module is positioned perpendicular to the jig with a positioning mechanism on the jig where it fabricates the first longitudinal beam to approximately a 200-m length, and then stops. The beam then is "gripped" by rollers on the assembly jig and cut off. Then the automated fabrication module is moved along a track on the side of the assembly jig until it is in position to fabricate the second longitudinal member, adjacent and parallel to the first, in the same operational manner. This sequence is repeated until the fourth longitudinal member is completed.

As shown in figure IX-2, the automated fabrication module is then rotated into position to fabricate the first cross member. After it is completed, the cross member is joined to the longitudinals by an Orbiter crewmember using a portable ultrasonic spotwelder (16 places — where the cross member and longitudinal beam cap members cross each other).

The partially constructed structure is then driven "across" the assembly jig by the retaining rollers until the longitudinals are in position relative to the automated fabrication module for fabrication and attachment of the second cross member in the same manner as the first. These events are repeated until installation of the last cross member, thereby completing the construction of the structure.

After completion of the test structure, various engineering tests and experiments will be performed while it is attached to the Orbiter to evaluate the construction process and the response of a large, lightweight structure to typical operational load simulations.

Flight Projects - In the SPS technology advancement program, each of the development objectives would be met with the simplest test format which could satisfy that test objective. As much testing as possible would be done on the ground, with only those experiments requiring the unique environment of space being forced to orbit for accomplishment. Some of the requirements for space experiments need the operation of two or more subsystem elements, and initial evaluation indicates that all these experiment requirements can be satisfied by grouping them conceptually into three flight projects which would use the Shuttle in the 1984-1987 time frame. The following section describes these three flight project concepts which have been identified to satisfy the system development requirements of a reference 1995 operational SPS system.

The first is a Microwave Energy Transmission Test Project which can satisfy experiment and development objectives in the following four primary areas.

a. Mirowave power transmission system

(1) Investigation of thermal effects on the transmitting antenna

(2) Test and evaluation of phase control system

(3) Power transmission efficiency

C-2

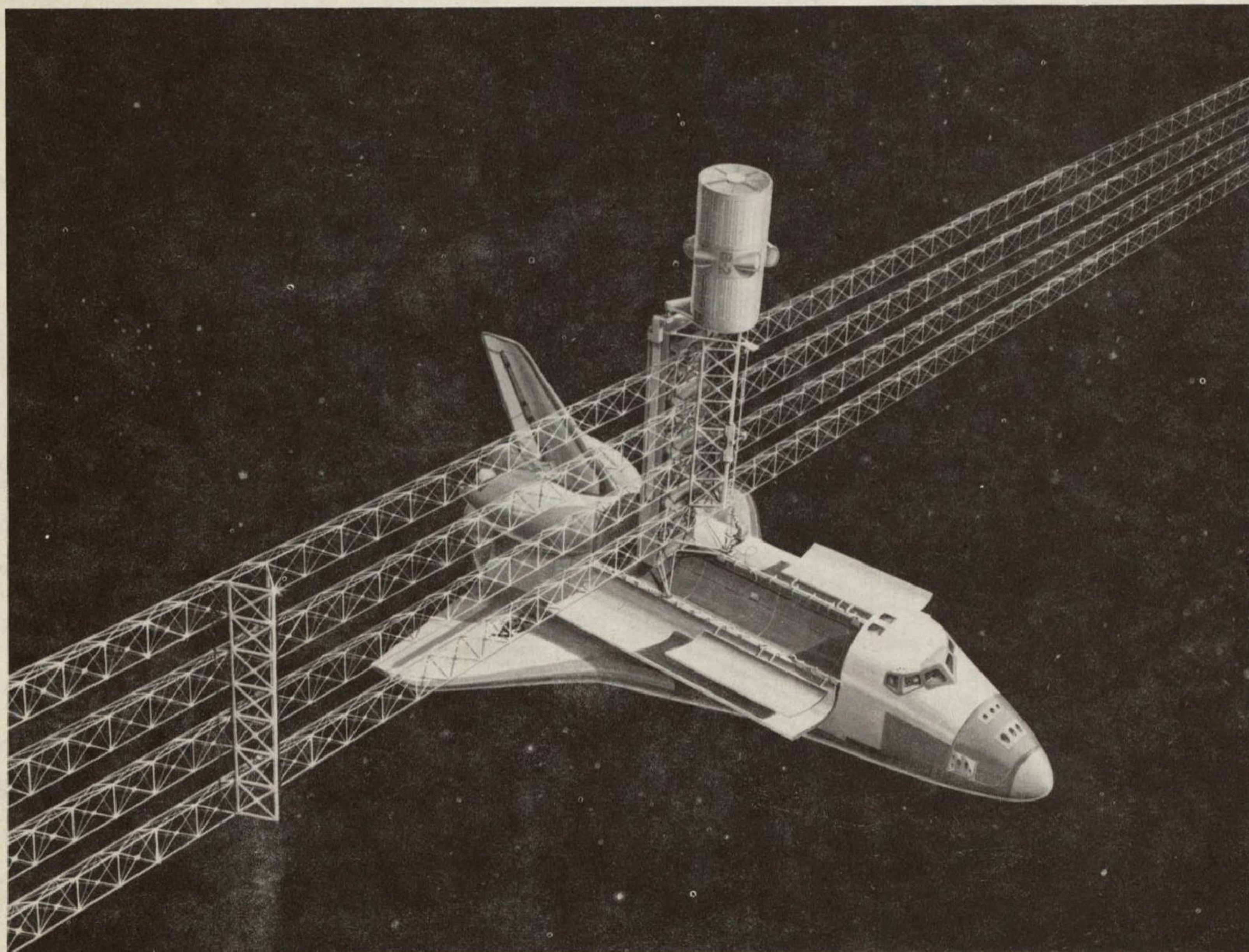


Figure IX-2.- Space fabrication experiment.

b. Photovoltaic power generation

(1) High-voltage dc utilization and switching

(2) Investigation of high-voltage power loss to surrounding plasma

c. System construction test and evaluation

(1) Automated fabrication process

(2) Large element assembly

(3) Large structures deployment

d. Space structures

(1) Investigate ultra-lightweight large structures

(2) Investigate structure-control system interaction

In this flight project concept, a large power module capable of generating dc power in the 200-500 kW range supplies electrical power across a rotating interface joint to a test transmitting antenna made up of several 3 m x 3 m subarrays. The antenna could be operated in two separate test configurations for thermal and phase control tests. The center subarray would contain four klystron microwave power generators, and the other surrounding subarrays would each have one. Operating the four center klystrons at full power and the others near half power would approximate the thermal conditions on an operational 1-km-diameter antenna. Power would be transmitted to a space test rectenna which could be a structural frame with rectenna element sensors mounted at strategic points and a phase control transmitter in the center. Transmission would be made at a range of about 500 m for near-field tests and 16.5 km for far-field tests. The objective of the microwave transmission tests are oriented toward a total microwave system performance evaluation using suitable test instrumentation, not the collection of a large amount of the transmitted power. The system could by modified slightly to provide intermittent power to the ground for a few minutes each orbit where a 300-m-diameter rectenna could collect approximately 500 W peak from an altitude of 300 n. mi.

As shown in figure IX-3, the large power module could be constructed in space using the automated fabrication equipment and techniques developed in the space fabrication experiment utilizing the Shuttle as a construction base. Antenna subarrays would be assembled on orbit into the test antenna configuration using the Shuttle RMS. The assembly jib is left attached to the power module during construction, and it contains all the necessary subsystems for orbital operations of the power generating system, and a docking or berthing system to allow subsequent Shuttle return flights. The space rectenna can be deployed from the Orbiter in orbit using a structure specially designed for folding into the payload bay in high-density form.

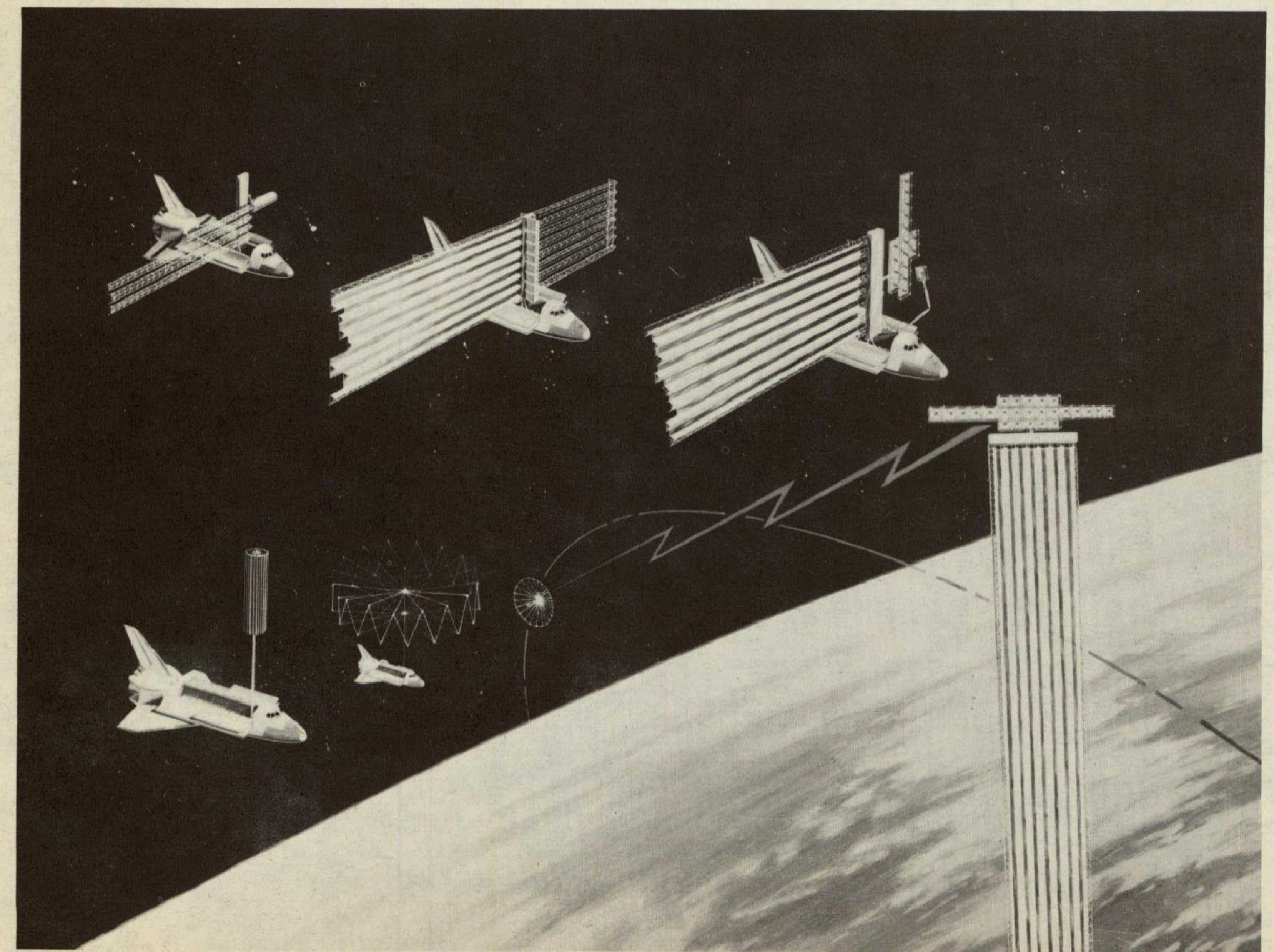


Figure IX-3.- Microwave energy transmission project.

Construction of the microwave test project could be accomplished within four Shuttle flights and could begin about 1984 with tests occurring in 1985. After completion of the project objectives, the large power module would be placed into service as a space utility power system for other objectives and applications.

The second flight project is a Phase Control/Ionosphere Test which is needed to evaluate the MPTS phase control system from GEO and involves the placement of a deployable crossed-array transmitting antenna and a power supply in GEO using the Shuttle and the IUS orbital transfer vehicle. Phase control evaluation tests would be performed at low power levels using high-gain receiving antennas on the ground. The tests would also be run in conjunction with ionosphere heating tests using the Arecibo (or Platville) facility in order to investigate phase control signal/ionosphere interaction. These tests could be scheduled in the 1986-1987 time period and would probably be preceded by LEO-to-LEO transmission tests using the same crossed-array configuration.

A third project, the Scaled Integrated System Flight Project, accomplished the final proof-of-construction concept test using the same construction facility concepts and construction processes and techniques planned for a full-scale operational SPS. Whereas previous construction experiments and projects utilized the Orbiter as a construction base and extravehicular crewmen in the fabrication process, this flight project uses the Shuttle as a logistics vehicle only and requires a construction facility and fully automated fabrication equipment. The resulting scaled-SPS test article provides an end-to-end operational test of the construction and operation of a space power system, and provides the design verification and confidence, to proceed to a GEO commercial demonstrator or operational SPS. The scope of this flight project is dependent largely on subsequent development planning, but would likely provide peak intermittent power in the 2 to 10 megawatt range to a ground rectenna from LEO.

Scaling Considerations for LEO Test of SPS Structure - As currently envisioned, the SPS structure will be designed for stiffness as required for maintaining shape and relative orientation. This can be achieved with efficient, lightweight structural concepts which are adequate for space application, yet not capable of supporting their own weight under terrestrial gravity. This precludes ground testing and points to the need for space testing for structural performance, fabrication precision, control/structure interactions and potential thermal/structural interactions. (A design approach to minimize thermal/structural interactions would be the use of materials and/or geometric arrangements which virtually eliminate thermal distortions.) Although geosynchronous orbit is unique from the standpoint of the overall system kinematics and power transmission, it appears that LEO offers many significant advantages for a scale model structural test of the system and/or its components. The basic objective of a scale model structural test would be to verify the capability to predict analytically the structural performance of the scale model system and, thereby, the full-scale SPS structure and associated systems. A scale model test in LEO should be preceded by numerous small component tests (compression elements, cables, joints, assemblies, subarrays, etc.) as

required to build a level of understanding and confidence. The engineering confidence obtained through a scale module test will be proportional to the degrees of similitude achieved. Table IX-3 summarizes a scale test approach and general scale system characteristics. The supporting analyses for the scaling factors shown in the table are included in section IX.B.3.c of volume II of this report.

3. Space Transportation - Low-cost transportation is a key to the economic viability of the space power concept. Very large systems would ultimately be required to achieve minimum cost of electricity. The Shuttle, shown in figure IX-4, will be adequate for initial space experiments and major LEO space projects. The phase of space projects to be conducted at geosynchronous orbit would require an extension of the Shuttle system to provide greater payload capability and an orbital transfer vehicle to transport any test articles to geosynchronous orbit and, also, to transport a small crew of men for short periods to assist in the deployment/assembly of test articles. This orbit transfer activity would require and demonstrate a refueling capability in LEO, travel to geosynchronous orbit, and return to a LEO base for transfer to the Shuttle and return to Earth. Development and demonstration of this capability (LEO to geosynchronous orbit and return) with its space facility and operations requirements are considered desirable prerequisites to commitment to the large-scale program activity.

The present Shuttle system lends itself to a growth configuration as shown in figure IX-5 with considerably increased payload and reduced cost per pound. Such a system could be effectively utilized in geosynchronous projects and also possibly for large-scale demonstration powerplants (500 to 1000 MW) if such size systems were deemed desirable.

A chemical orbital transfer vehicle configuration is presented for use in support of concept evaluation projects. This system could provide a technology base for a larger "full-scale" system, and also could be used during a commercial phase as a personnel carrier.

Only chemical orbital transfer vehicles are shown in figure IX-5. As discussed in various areas of this report, electric thrusters are considered a viable competitor at the present time for use in moving major modules of the system to geosynchronous orbit. If this option is pursued, it would be a necessary part of the conceptual evaluation projects to demonstrate this type of system.

C. Related Activities

Two studies have been conducted outside specific SPS concept evaluation studies which provide material pertinent to the SPS. One study was the "Space Station Systems Analysis Study" and the other was an "Orbital Construction Demonstration Study." These studies are particularly applicable to space projects which might be conducted during a technology advancement phase of an SPS program. They deal primarily with the construction in space of SPS test articles and the development of techniques and technologies involved in such space construction activities.

TABLE IX-3.- SCALING FACTORS FOR SCALE MODEL LEO

STRUCTURAL TEST OF GSO SPS ($S \sim 15$)

Parameter	$\frac{GSO}{LEO}$	Comments on scale model
Configuration		
Length	s	$\sim$ 1.8 km (1 n. mi.)
Width	s	66 m diameter antenna
Depth	s	
Mass	s^2	$\sim 3.5 \times 10^5$ kg (12 Shuttle payloads)
Mass/surface area	1	Full-scale hardware eg. solar cells
Power	s^2	$\sim$ 1/225
Power distribution system		
Length	s	
Width (or diameter)	s	
Thickness	1	
Voltage	s	$\sim$ 2700 volts
Current	s	
Resistance	1	
Operating temperature	$\sim$1	
Structural members		
Length	s	
Width or diameter	s	Similar buckling criteria
Thickness	1	Minimum gauge
Stress	1	
Strain	1	
Angular distortion	1	
E/ρ	1	Same material
Excitation frequencies	1/s	Relative to orbital frequencies
Control frequences	1/s	
Natural frequencies		
Structure	1/s	
Antenna	1/s	
Truss	1/s	
Col/cable	1/s	
Array		

TABLE IX-3.- Concluded

Parameter	$\frac{GSO}{LEO}$	Comments on scale model
Forces (s desired)		
Control	s	
Gravity gradient	s	
Current interactions	s	
Solar radiation	s^2	X Does not scale appropriately
Aerodynamic drag	$\sim 10^{-20}$	X Does not scale appropriately but might be used to simulate solar radiation
Moments (s^2 desired)		
Control	s^2	
Gravity gradient	s^2	
Magnetic loop interaction	s	X Does not scale appropriately
Accelerations		
Linear	1/s	
Angular	1/s	
Thermal		
High temperatures	$\sim$1-.8	
Low temperatures	$\sim$1-.3	
Penumbra transit time	1.2s	
Characteristic thermal response time	$\sim$1	X Does not scale appropriately
Achievable flatness	?	
Damping	?	
Measurement	?	

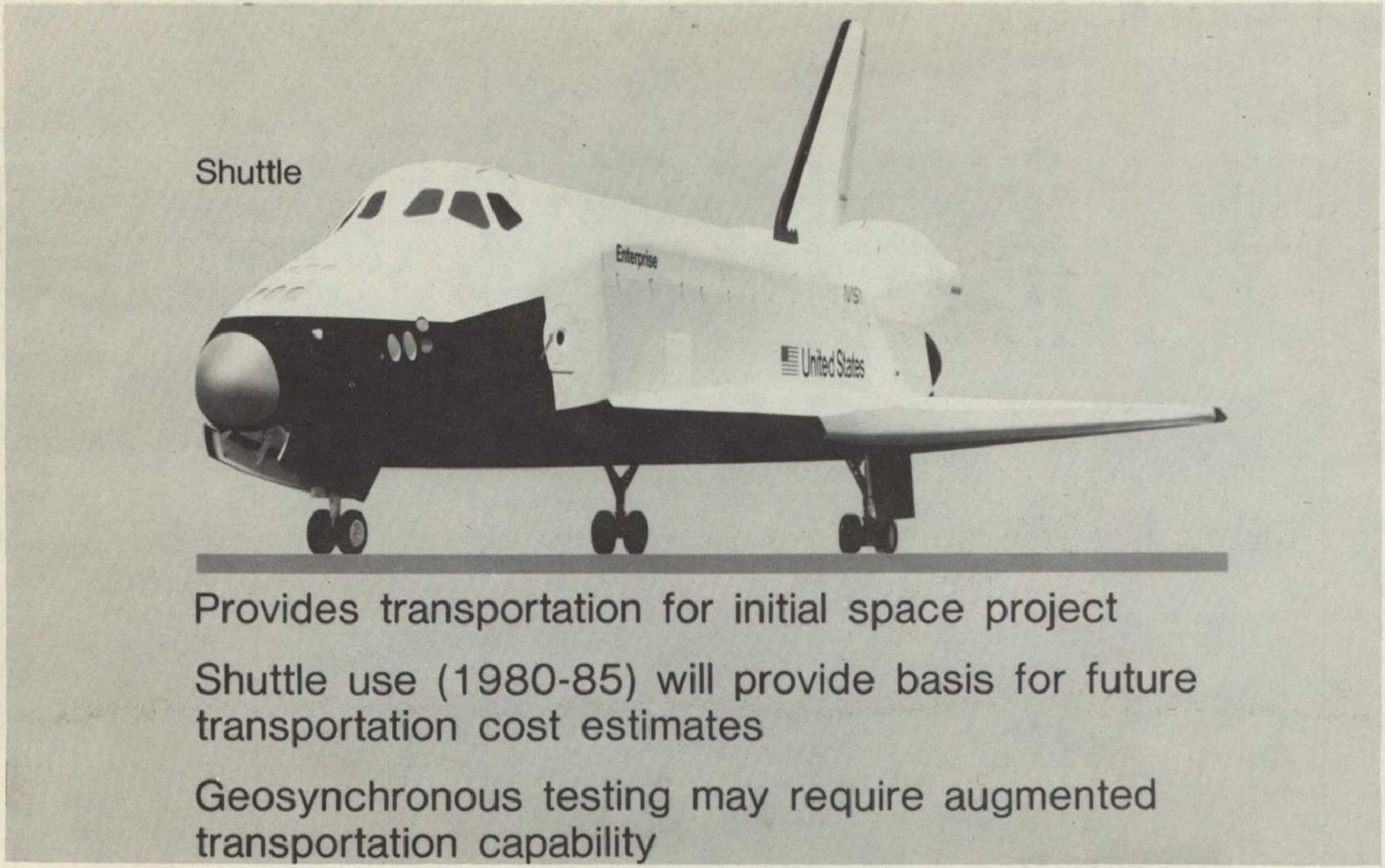


Figure IX-4.- Space transportation.

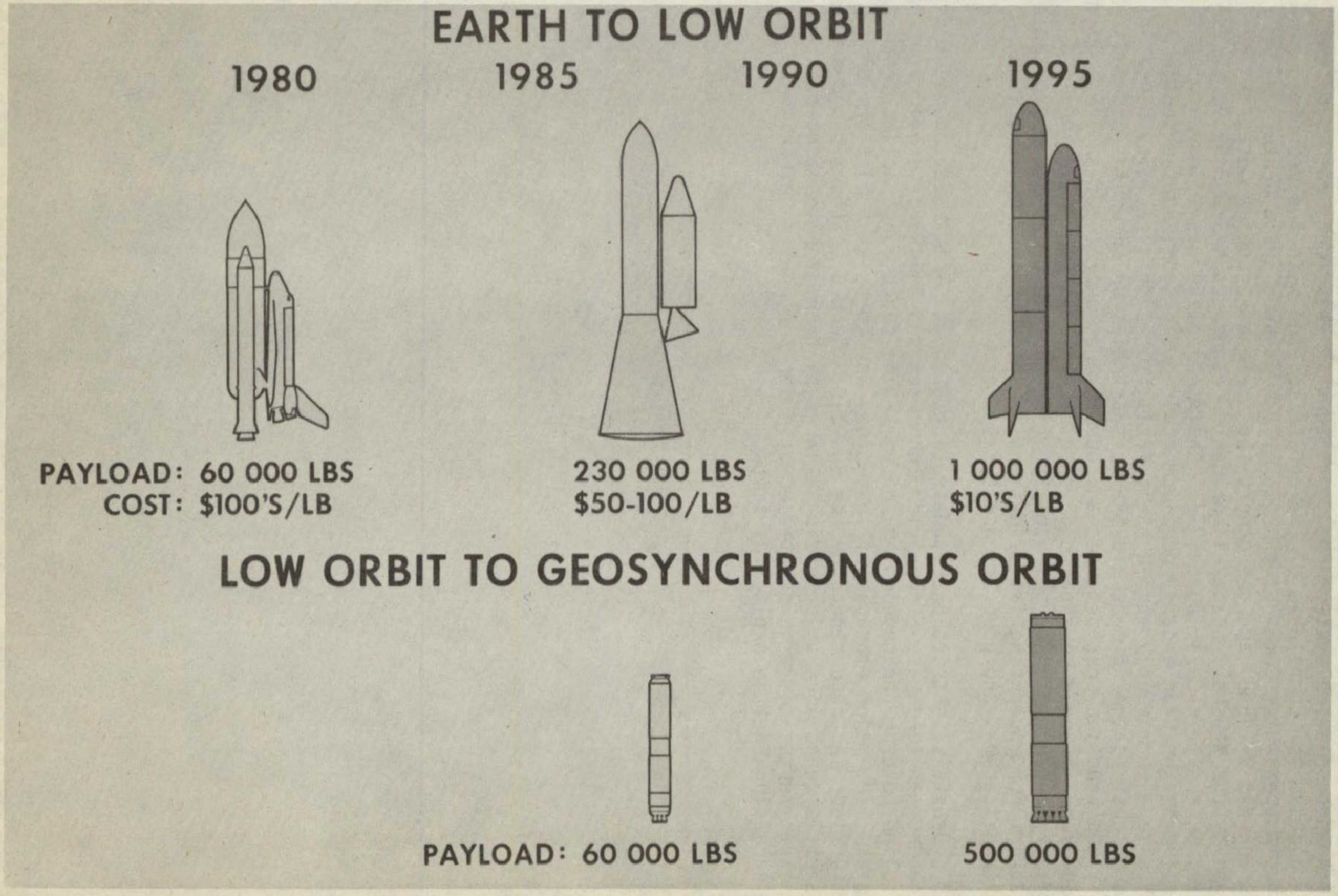


Figure IX-5.- Space transportation.

1. Space Station Systems Analysis Study - This study was conducted in parallel with the release of two contracts; one with the McDonnell Douglas Astronautics Company, managed by the Johnson Space Center (contract NAS 9-14958) and the other, the Grumman Aerospace Corporation, managed by the Marshall Space Flight Center (contract NAS 8-31993). These studies were completed in June 1977. Their objective was to develop cost effective options for orderly developmental growth from Shuttle sortie flights to a permanently manned space facility. Such a facility would perform construction of subscale SPS test articles which would test and verify construction, performance, and operational aspects of an SPS program. In addition, it would be capable of assembling large communications and radiometry antennas to serve a variety of Earth needs. It would provide a platform for conducting investigations of space processing as well as other applications and pure science activities.

2. Orbital Construction Demonstration Study - This study, conducted by the Grumman Aerospace Corporation (contract NAS 9-14916), provided a baseline concept for developing and verifying space construction technologies. The major emphasis of this study was to build a platform or factory floor in space tended by the Shuttle. Such a platform could enhance the Shuttle capability by providing a large platform for mounting construction experiments and large quantities of power for running experiments and increasing Shuttle orbit stay times.

X. PROGRAM COST

A. Scope of the Cost Estimating Effort

The program cost range presented in the report titled "Initial Technical, Environmental and Economic Evaluation of Space Solar Power Concepts" was derived by defining a fundamental work breakdown structure and estimating the cost range of all items in the work breakdown - such as solar cells, transportation, and satellite components - to develop a range of total program costs. This process was extremely cumbersome and time consuming because of the magnitude of the accounting task. Thus, a goal was set to automate this process during the past work year. Once this automation process was developed, sensitivity studies were conducted to identify key cost drivers within the SPS program.

In addition to this effort, cost comparisons were made between the costs developed by the JSC and those developed by the Marshall Space Flight Center (MSFC), the Jet Propulsion Laboratory (JPL), and the ECON Corporation. Cost information for these comparisons was obtained from reports published by the various Centers. Next, the JSC system cost estimates were refined by using a more detailed work breakdown structure and more sophisticated estimating relationships, together with historical learning data, to produce a set of estimates of design, development, test, and evaluation costs, first unit costs, recurring costs, and operations costs of an SPS program.

B. Cost Sensitivities

The results of analysis conducted during the last year are given in the following discussion. A detailed discussion of the methodology used and all data obtained may be found in volume II, section X.A.

1. Cost Driver Identification

The SPS cost computer model was first calibrated by repeating the cost analysis of the conceptual SPS program, had been manually estimated to produce power at a cost of 59 mills/kWh. Individual items in the work breakdown structure were then varied by independently reducing the unit costs and unit weights by 50 percent. The results of this analysis are shown in figure X-1 as a ranking of the top 25 cost drivers in an SPS program. For example, if the HLLV unit flight costs could be reduced by 50 percent, from $23 million per flight to $11.5 million per flight, the 59-mills/kWh nominal power cost could be reduced to 50 mills/kWh, if all other cost variables are held constant.

2. Solar Cells

The solar cells were studied in detail because both their mass and unit cost appear in the top 10 of the 25 cost drivers shown in figure X-1.

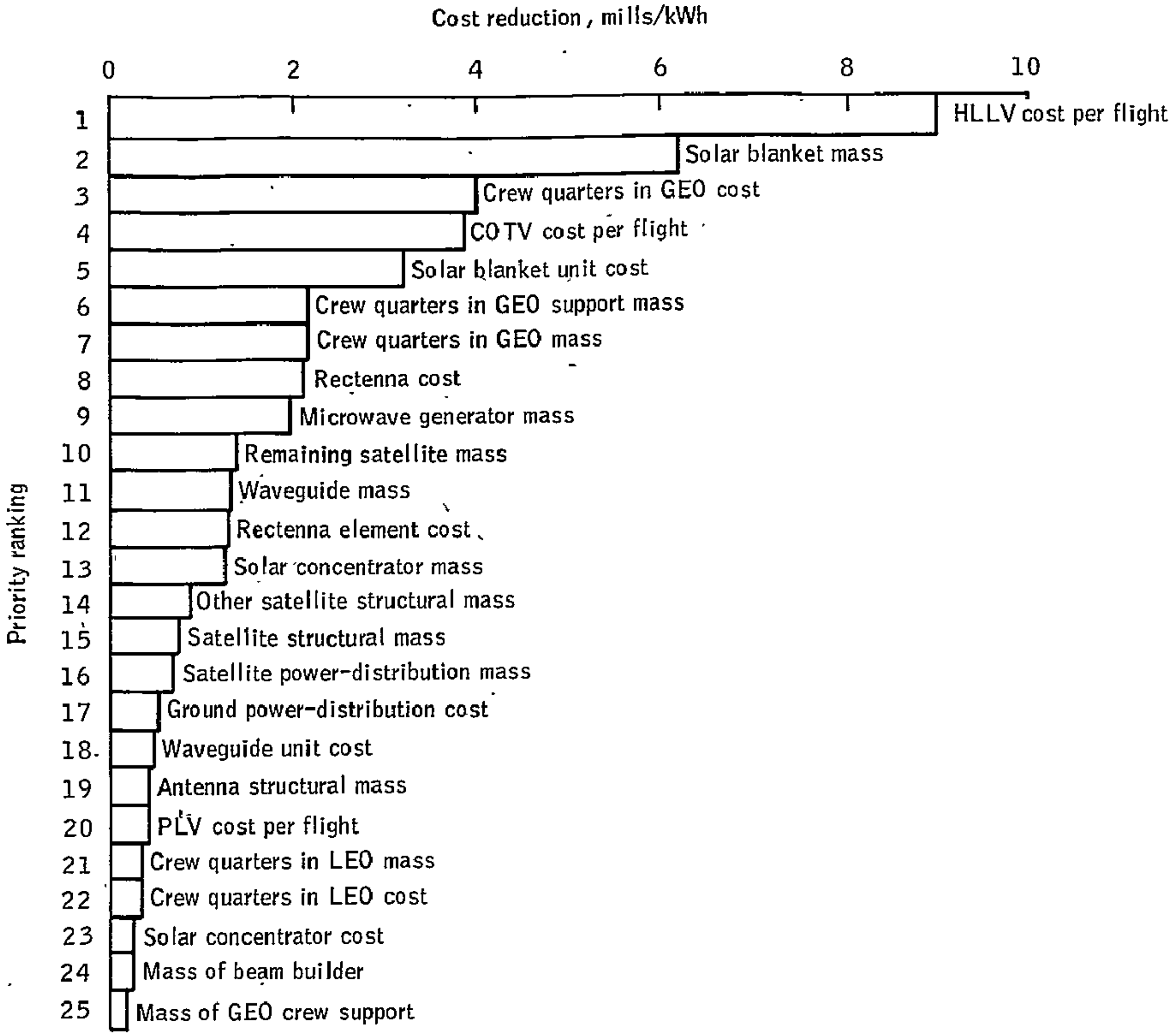


Figure X-1.- Major SPS cost drivers.

Figure X-2 shows the effect of solar cell cost, mass, and performance on a 59-mills/kWh SPS electricity cost. Concentration ratios of both 1 and 2 are considered. These data do not include any allowance for degradation of either mirrors or solar cells. It should be noted that, at higher efficiencies on the order of 15 percent, the cost delta between concentration ratios of 1 and 2 is 12 mills/kWh. If, however, the lower concentration ratio results in more simplified manufacture and assembly, the cost advantage of the higher concentration ratio may be substantially reduced. For comparison purposes, a laboratory gallium arsenide solar cell that is currently being tested is also presented in figure X-2.

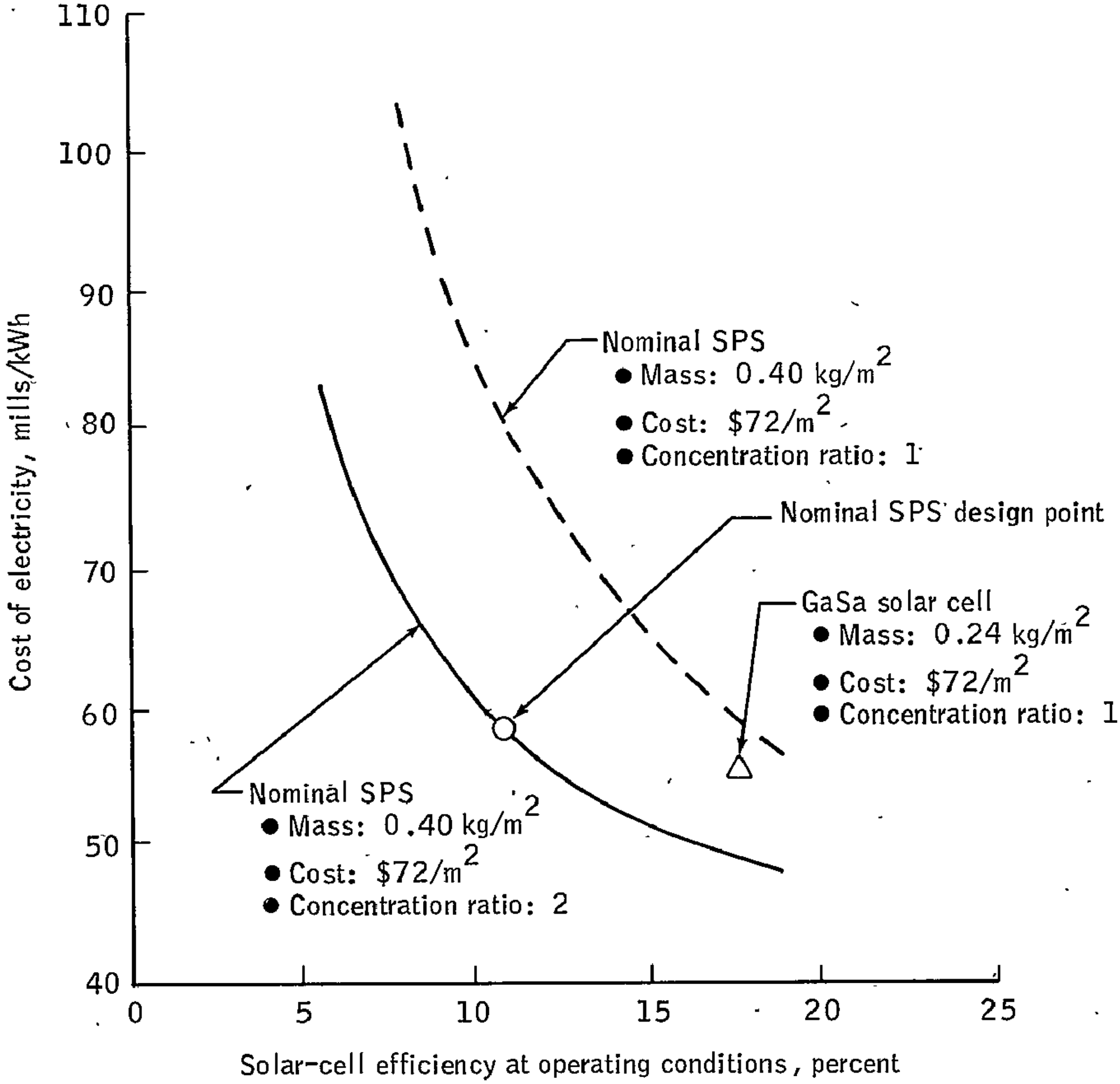


Figure X-2.- Effect of solar cell efficiency on power cost.

3. Rate of Return on Equity

The rate of return used by typical investor-owned electric power companies is, on the average, 15 percent. The cash flow of an SPS producing power at 59 mills/kWh at a rate of return of 15 percent is shown in figure X-3. In this cash flow diagram, DDT&E is amortized over a 30-year

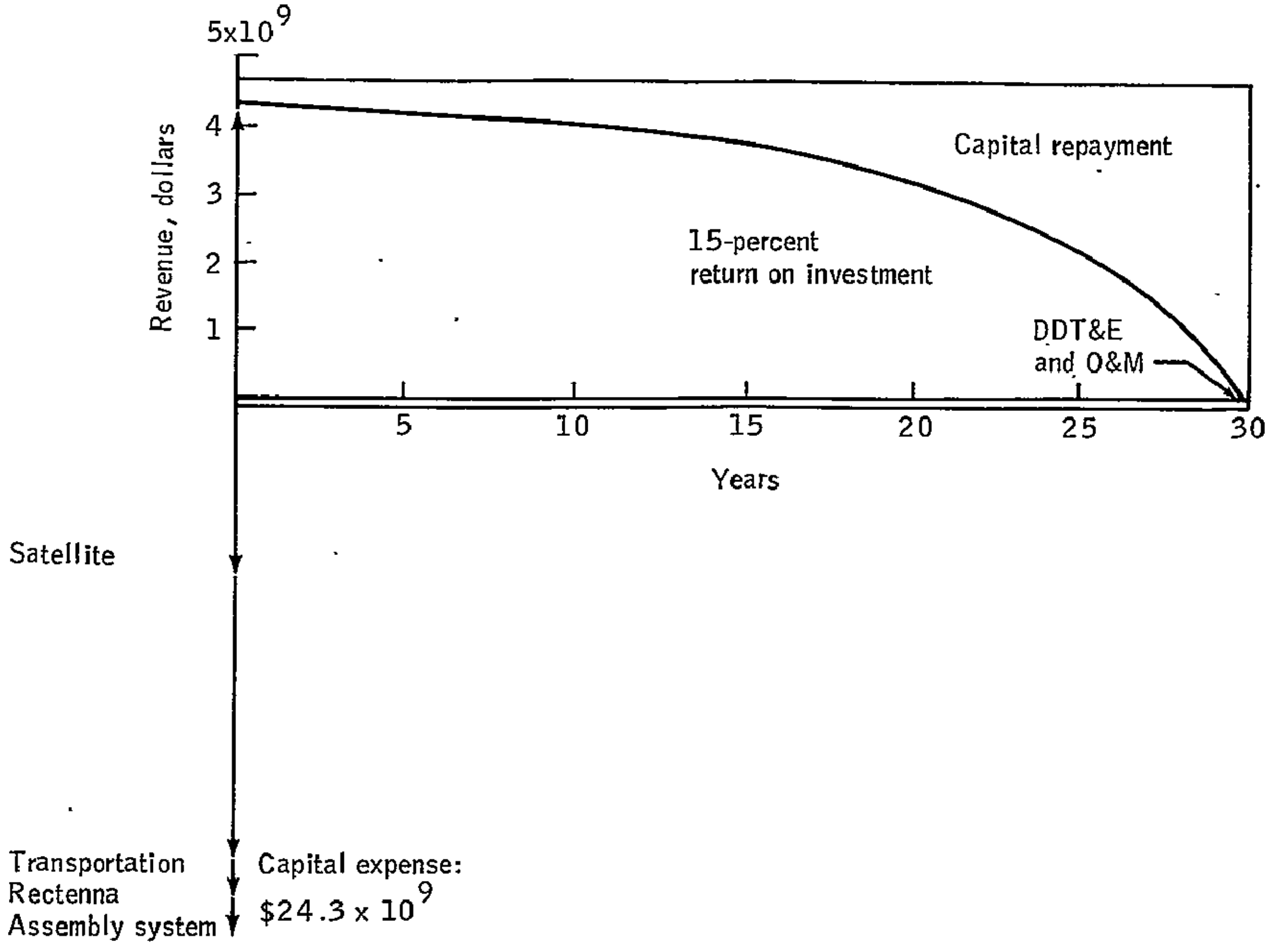


Figure X-3.- SPS cash flow.

period. Typically, this 15 percent rate of return is broken down as follows.

Item	Percent rate of return
Cost of money	7.0
Income tax	3.0
Depreciation	2.5
Other taxes	2.2
Insurance	.1
Working capital	.2
Total	15.0

A rate of return of 15 percent is, therefore, essential if the SPS is to operate as a typical investor-owned power production facility.

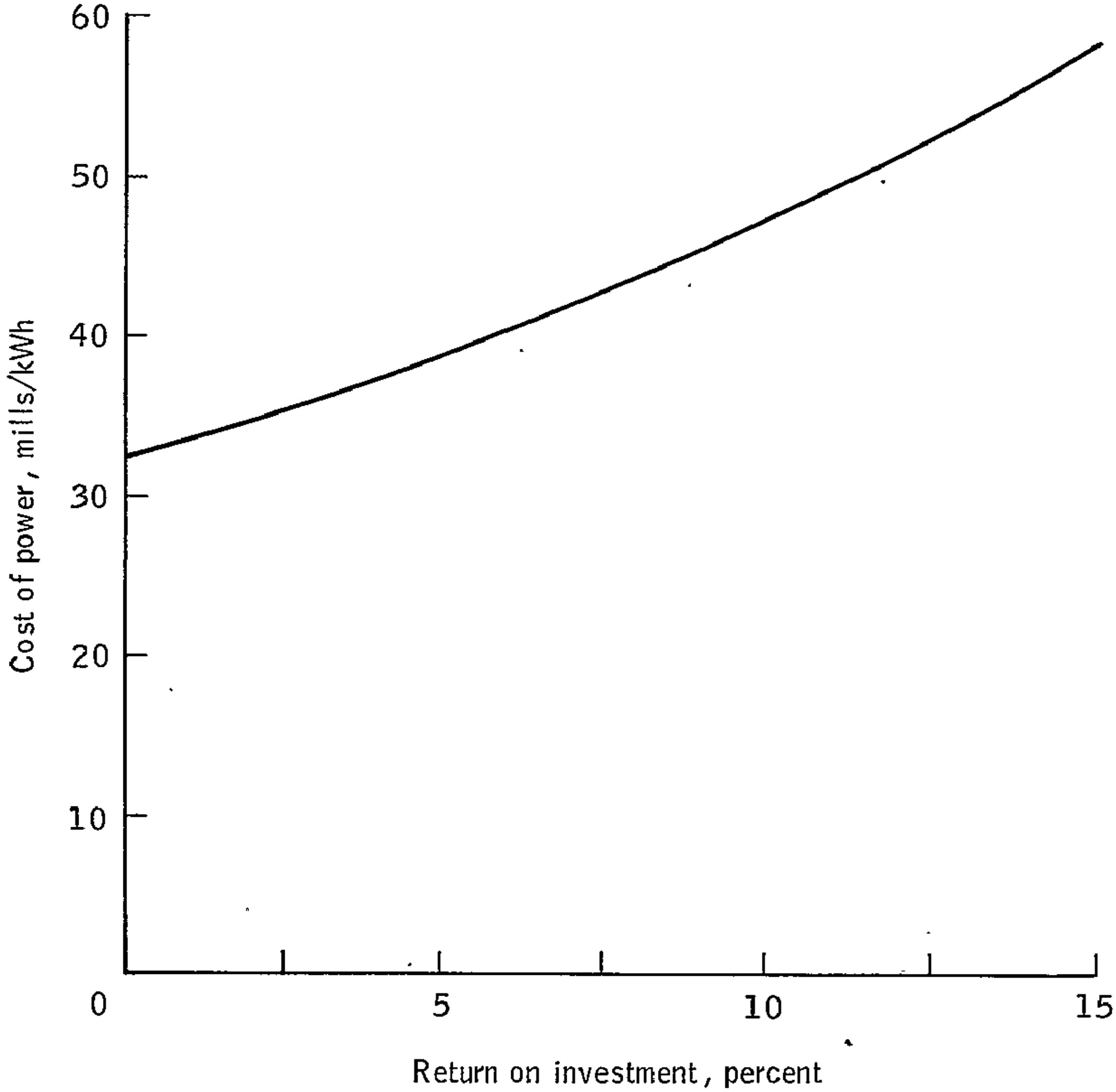


Figure X-4.- Effect of return on investment on power cost.

Figure X-4 shows the effect of varying rate of return on the cost of electricity. It should be noted that rate of return has a bigger effect on the production cost of electricity than any of the key cost drivers identified in figure X-1.

4. Effect of Satellite Implementation Rate

A study was conducted to determine the effect of varying the number of satellites installed per year on the cost of electricity. As shown in table X-1, the number of satellites installed per year can have

TABLE X-1.- EFFECT OF SCENARIO B ON COST OF POWER[a]

Parameter	Cost, mills/kWh
50-year operation:	
4 satellites/yr	51
Scenario B	52
31-year operation:	
4 satellites/yr	54
Scenario B	59

[a]112 satellites operating.

a significant effect on cost. This effect occurs because high-cost items such as space construction bases are not fully utilized and amortized at low implementation rates. In the case wherein the rate of implementation gradually builds up to seven per year at the end of 30 years, the construction bases were not fully utilized after the 13th year. A more optimal utilization of these bases could be accomplished by installing satellites at a constant rate of four per year throughout the 30-year life of the program. This approach reduces the cost of power by 5 mills/kWh. Table X-1 also shows the effect of the SPS implementation program from 30 to 50 years. This concept results in some savings, but they are not as significant as those that would result from more optimal utilization of space construction bases.

5. Design, Development, Test, and Evaluation (DDT&E)

The DDT&E of the SPS requires a large-scale development effort in diverse areas such as large-volume manufacture, booster technology, assembly equipment, space stations, and solar cells. It would, therefore, be appropriate to amortize these costs over production-type satellites rather than allocating these costs to early demonstration units. The contribution of DDT&E to SPS power costs as a function of the number of satellites installed is shown in figure X-5. The contribution of DDT&E to total power costs begins to level off after about 60 units have been installed.

6. Comparison of JSC, MSFC, and JPL Cost Estimates

As discussed previously, many factors can affect the bottom-line cost of electricity in mills per kWh. Independent cost estimates may vary significantly because of differences in basic assumptions, such as rate of return on equity, the method of amortizing DDT&E costs, implementation rates, and many other costs or items that affect costs. Table X-2 is a

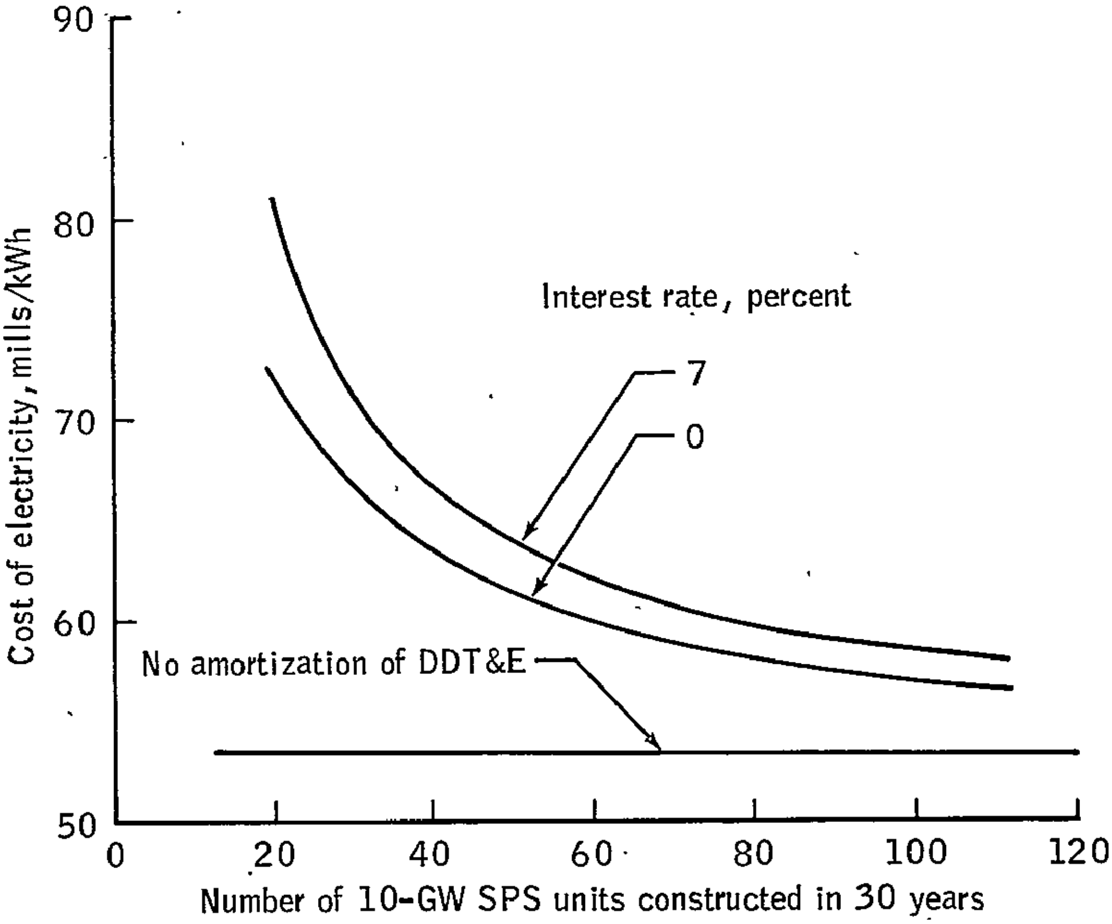


Figure X-5.- Effect of DDT&E amortization on cost of electricity.

matrix display of SPS cost estimates made by three NASA Centers and ECON, Inc. The MSFC, JSC, and ECON efforts are based on SPS studies, each with a different set of satellite design assumptions. The JPL estimate is based upon a particular selection of parameters from the JSC, MSFC, and ECON system studies and upon some reassignments of the values on various items such as solar cell efficiency, SPS load factor, weights, and unit costs. In most cases, these values were reassigned in a direction that forced the cost of electricity upward.

C. Updated JSC Cost Estimates

The initial engineering estimates of the SPS program cost were based on the conceptual design produced last year. This estimate resulted in a bus bar cost of electricity range of 29 to 115 mills/kWh. An updated, single-point cost estimate was made this year with the use of a more complete work breakdown structure and an expanded cost-estimating data base of estimating relationships. This approach produced an estimate of 45 mills/kWh, which is within the cost range estimated last year. It is planned to further improve the confidence level of this estimate through

TABLE X-2.- COST COMPARISONS

(a) Cost of subsystem[a]

Variable	Location				
	ECON	MSFC[b]	JSC[c]	JSC[d]	JPL
Transport to GEO, $/kg	182	182	152	31.79	145
Solar blanket, $/kW	--	834	300	130	921
Solar blanket, $/m^2	54	59	42	18.2	104
Surface density, kg/m^2	--	0.61	0.62	0.62	0.95
Microwave system, $/kW	368	559	329	766	520
Solar blanket efficiency, percent	--	13.7	10.3	10.3	8.4
Microwave system efficiency, percent	60	58	60.6	60.6	60
Overall system efficiency, percent	--	7.9	5.36	5.36	4.2
Load factor	0.95	0.85	0.92	0.92	.64
Return on investment, percent	7.5	7.5	15	15	15
Construction time, yr	1	2	1	1	6

[a]Nominal data.
[b]Adjusted life-cycle cost.
[c]1976 cost estimates.
[d]1977 cost estimates based on learning curve data and a more detailed work breakdown structure.

(b) Cost of power

Source of estimate	Capital Investment					
	$/kW			mills/kWh		
	Low	Nominal	High	Low	Nominal	High
ECON	2440	2840	2980	30	50	59
MSFC	2316	4486	9190	32	62	127
JSC[a]	1400	3000	5780	29	59	115
JSC[b]	--	2287	--	--	38	--
JPL	4600	5600	7153	40	118	485

[a]1976 cost estimates.
[b]1977 cost estimates.

more complete definition of subsystems and components and a refinement of cost-estimating techniques during the next year. The goal will be to narrow the range of cost estimates.

Detail-costing ground rules and assumptions are presented in volume II for each configuration, and major points of emphasis are discussed below.

1. Configuration Work Breakdown Structure and Traffic Model

The SPS configuration costed was the truss configuration, with the use of nominal baseline weights. The HLLV was a propane/liquid-oxygen booster, with the Space Shuttle main engine (SSME). The COTV was based on the LH_2/thermal-electric-arc jet concept. Two personnel and priority-cargo launch vehicle configurations were costed: F-1 engines in the LRB and a new propane/liquid-oxygen engine in the PLV; estimates for the propane/liquid-oxygen vehicle were those included in the cost summaries. Concepts for the construction base, construction devices, and facilities were largely designed by the estimators, with inputs from the JSC Engineering and Development Directorate. The rectenna design was based on Raytheon design information.

The work breakdown structure for all elements costed is given in table X-3. Twelve first-tier elements and more than 50 second-tier elements, each of which was costed individually to a lower level of detail, were involved. Scenario B was assumed in the development of schedules for vehicle DDT&E and deployment.

To aid in communicating numbers of the magnitude involved, major estimates are presented in dollars per kilowatt of SPS power. The DDT&E and TFU costs are presented for all major items; all costs are in constant fiscal year 1977 dollars.

2. Costing Methods Used

Costing methods used were primarily parametric. Hundreds of estimating relationships were used and will not be presented here (most are given in vol. II, however). For aerospace vehicles, existing data bases are considered to be very good, particularly for items using current technologies (e.g., structures and engines) or those using technologies with familiar evolutionary patterns (e.g., certain avionics elements). When time permitted, especially for the more costly items, multiple techniques were used; and results were cross-checked with results of other studies, where available.

For certain very costly items (the reception system and the SPS satellite itself), the RCA PRICE model was used to provide an independent set of estimates; because of the lack of precise analogies for these items, the uncertainties are probably the highest of all.

All transportation elements were costed to the subsystem level, with the use of standard NASA aerospace methods. These estimates are considered accurate and as reliable as the current vehicle descriptions.

TABLE X-3.- WORK ELEMENTS FOR SOLAR POWER SATELLITE

1.1-Satellite	1.2-Transportation	1.3-Fabrication assembly	1.4-Ground systems

1.1.1-Collection
 	
Solar cells
Concentrators
Support structure
  Primary
  Secondary
Power collection
Power management
  Protection
  Switching
  Regulation
Rotary joints
Instrumentation
 	
1.1.2-Transmission
 	
Structure
  Primary
  Secondary
Power distribution
  Conductors
  Switchgear
Microwave conversion
  Generators
  Waveguides
Control System
  Pointing
  Phase control
Instrumentation
	1.2.1-HLLV
	
	Vehicle
	Fuel per flight
	Launch operations
	Recovery operations
	Refurbishment
	
	1.2.2-COTV
	
	Vehicle
	Fuel per flight
	Refurbishment
	
	1.2.3-PLV
	
	Vehicle
	Fuel per flight
	Launch operations
	Recovery operations
	
	1.2.4-POTV
	
	Vehicle
	Fuel per flight
	Refurbishment
		1.3.1-Space construction base
		
		Space facility
		Ground support
		
		1.3.2-Solar collection fabrication and assembly
		
		Beam builders
		Reflector installers
		Solar cell blanket installers
		Conductor installers
		Mobile manipulator
		Docking modules
		
		1.3.3-Antenna fabrication and assembly
		
		Beam builders
		Conductor installers
		Subarray installers
		
		1.3.4-Fabrication and assembly support
			1.4.1-Transportation
			
			Launch and refurbishment facility
			Recovery facility
			
			1.4.2-Reception
			
			Land
			Site preparation
			Structure
			Dipoles
			Ground plane
			Power collection
			Power management
			  Inversion
			  Switchgear
			  Regulation

Because only very preliminary conceptual designs existed for the assembly station, designs were postulated on the basis of phase B NASA space-station studies, and modules were postulated for a variety of purposes (living, recreation, assembly, dispensary, etc.). Descriptions of the modules used are presented in volume II of this study. It should be remarked that no design optimization was performed for the assembly station.

Facility costs were based on a one-site desert launch complex with downrange recovery. The launch complex itself was extricated from the Saturn V complex 39 at the KSC.

3. Summary of Estimates

Results of this analysis are shown in table X-4 in cost per kilowatt (for 112 10-GW satellites) for all major program elements.

In order of cost sensitivity, the costs are as follows.

	Total costs, $/kW	Total costs, mills/kWh
1. Ground reception (rectenna)	945	18.9
2. HLLV	518	10.36
3. Satellite collection (solar collector)	397	7.94
4. Satellite transmission	242	4.84
5. Construction base	68	1.36
6. COTV	45	.9
7. PLV	31	.62
8. Satellite integration, test maintenance	15	.3
9. Facilities	13	.26
10. All other	13	.26
Total	2287	45.74

The relative magnitudes of the costs are portrayed in figure X-6, in which the dominance of the power collection, the ground reception and transmission systems, and the HLLV operations is clearly displayed. Certain components of these costs (e.g., collector instrumentation) are very large and are not fully explainable when the input weight data are examined.

TABLE X-4.- TOTAL COST SUMMARY FOR SPS

Item	$/kW (1977 dollars)			
	DDT&E	Production	Operations	Total
SPS	31.88	1442.84	812.25	2286.97
Satellite	(8.57)	(475.68)	(172.01)	(656.26)
Collection	2.83	289.63	104.69	397.15
Transmission	2.56	176.01	63.69	242.26
Software	1.88	--	--	1.88
I&T	1.30	10.04	3.63	14.97
Transportation	(15.81)	(127.81)	(450.36)	(593.98)
HLLV	12.24	83.51	422.42	518.17
COTV	1.46	38.05	5.32	44.83
PLV	2.11	6.25	22.62	30.98
Fabrication and assembly	(6.68)	(49.69)	(22.93)	(79.30)
Space construction base	4.69	43.56	19.28	67.53
Satellite assembly system	1.25	3.95	2.33	7.53
Antenna assembly system	.55	2.18	1.32	4.05
I&T	.19	--	--	.19
Ground system	(.82)	(789.66)	(166.95)	(957.43)
Facilities	--	10.78	2.02	12.80
Reception	.82	778.88	164.93	944.63

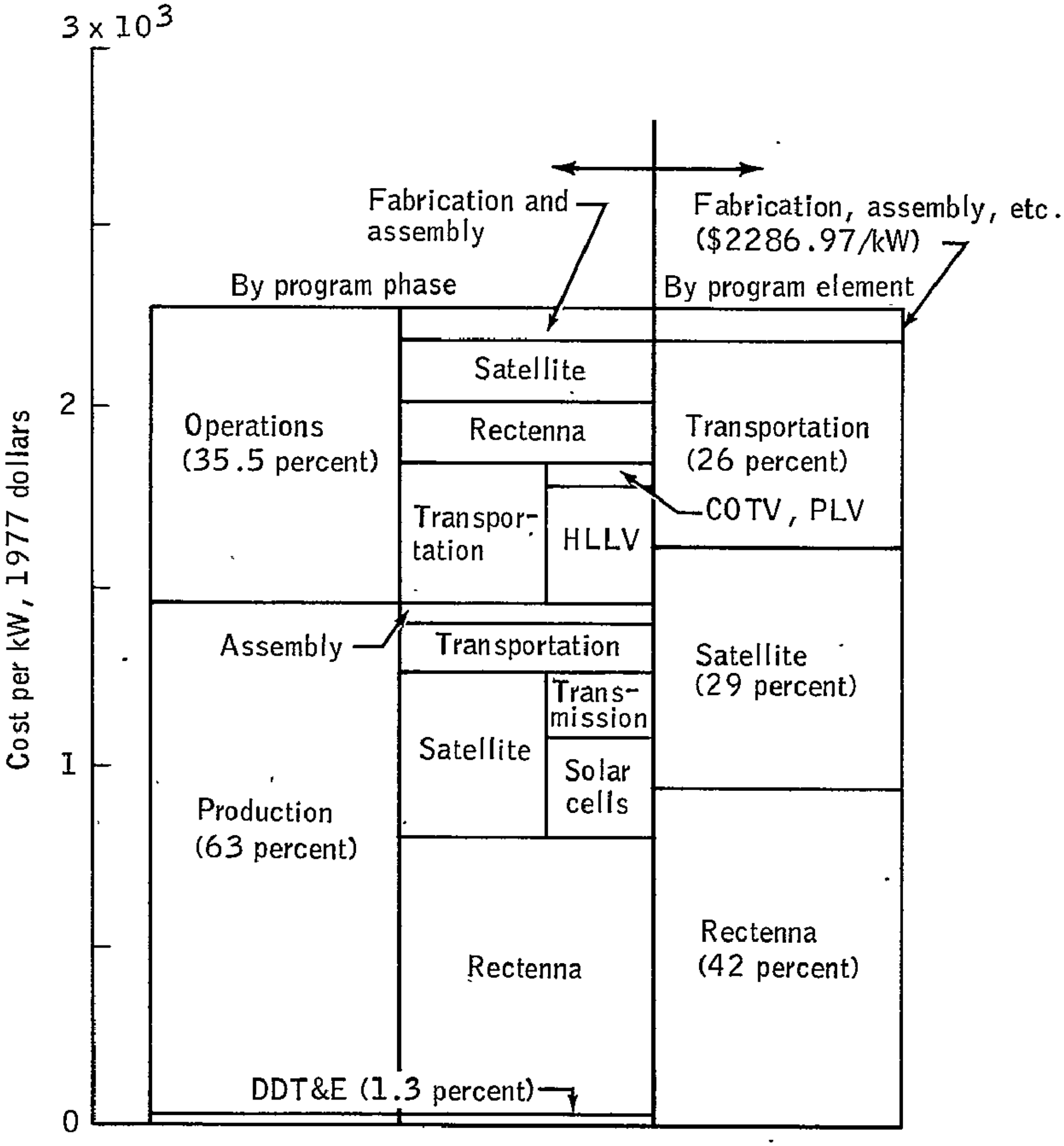


Figure X-6.- Summary of estimates.

XI. ALTERNATIVE SYSTEM COMPARISONS

To become a practicable electrical power source for the future, the SPS must be competitive with alternative sources from standpoints of cost, technology availability, and environmental factors.

Volume II of this report provides discussions of the various conventional and advanced technology power systems and their projected future utilization. This section provides a synthesis of the descriptive and characteristic information on each system, including the SPS. The objectives are to provide perspective among the various power system alternatives and to summarize the advantages and limitations of the SPS concept relative to alternative systems. The alternatives considered for analysis are shown in table XI-1.

The approach used was to develop comparative data for each system, sized at a plant capacity of 5 GW. This capacity was selected because it is the reference capacity of one SPS rectenna. It was not necessary that unit capacity be 5 GW; the 5-GW capacity could be obtained by multiple units of smaller capacity.

TABLE XI-1.- ALTERNATIVE POWER SYSTEMS

(a) Conventional systems

System	Percent of 1975 generation
Natural gas	17
Oil	18
Coal	44
Nuclear fission (LWR)	6
Hydroelectric	15

(b) Advanced systems

System	Percent of 1975 generation
Nuclear fission (LMFBR)	0
Fusion	0
Solar (terrestrial, space)	0
Geothermal	<<1
Ocean thermal	0
Wind	0
Oil shale	0
Bioconversion	0

It was also assumed that the various power system technologies could be made available by the 1995-2000 time frame. It is realized that uncertainty exists at present regarding the future of fusion power, the liquid metal fast breeder reactor (LMFBR), and oil shale development. For purposes of comparisons, these were assumed to be practicable candidates for the future, because no firm technical basis exists for excluding them at present. Also, most of the data utilized in this analysis were derived from sources that were advocates of the various technologies. In most cases, the data were accepted without criticism.

The comparison factors used were technological status, costs, and environmental considerations. Technological considerations included current (1976) status, economic size, expected commercial data, key problems, and potential or anticipated electrical energy production in the year 2000. Technology status in 1976 was expressed in terms of proven, demonstration in progress, laboratory, or conceptual.

Cost data were determined in terms of capital cost, fuel cost (as applicable), and operation and maintenance costs. These data were summarized in terms of cost of electricity (mills/kWh), using a 30-year lifetime and a 15-percent rate of return on investment in each case. The plant factor used in cost of electricity calculations varied from system to system, based on their design/operation characteristics.

Environmental comparison data were developed in terms of land use, water consumption, air pollution, waste storage or disposal quantities, and other factors as applicable.

A. Technological Status

Table XI-2 presents a summary of the technological status of the power-system alternatives. Most data are self-explanatory except economic size and potential and/or anticipated contribution in the year 2000. Economic size (expressed in megawatts) is the minimum plant capacity that results in lowest overall power-generation cost. This size may be dictated by the largest capacity component (e.g., steam turbine, generator) available or transportable. The value given for SPS (5000 MW) is based on very preliminary system-sizing studies, primarily related to microwave transmission considerations. The potential or anticipated contribution column of table XI-2 is the percentage of the year 2000 electrical energy demand (kilowatt-hr) that could be supplied by the given source. The year 2000 demand used to determine the percentages was 10×10^{12} kWh, from the projected Federal Power Commission data discussed in section III.

The general conclusion to be drawn from table XI-2 is that no single electrical power source will be used to the exclusion of other sources. Coal and nuclear—Light Water Reactor (LWR)—energy are proven technologies and they will produce almost 75 percent of the nation's electrical energy in the year 2000 according to the data source utilized. Another significant point is that less than 5 to 6 percent of the total electrical energy will

TABLE XI-2.- TECHNOLOGY STATUS AND PROJECTIONS

System	Technological status, funding ($ x 10^6), fiscal year	Economic size, MW	Expected commercial use	Key problems	Potential/anticipated contribution,[a] percent (year 2000)
Natural gas	Proven	600	Present	Fuel supply	6 to 7
Oil	Proven	600	Present	Fuel supply	7 to 8
Coal with stack gas cleanup	Research demonstrations $52, FY77	600	1978	Mining, transport stack gas cleanup	25
Oil shale	Pilot plant, $12, FY77	(b)	1980 to 1985	Water supply, plant sizing	3 to 6
Fission:					
LWR	Proven	600	Present	U_{235} supply, plant sizing	48
HTGR[c]	Demonstration, $0, FY77	1200	1985	U_{235} and Th_{232} supply, limited development	No estimate
LMFBR	Demonstration, $665	1500	1988 to 1990	Safety design, plant sizing, fuel process development	10
Fusion	Research, $392, FY77	5000	After 2000	Basic design for net energy production with sustained operation	0
Ground solar	Laboratory to pilot plant, $102, FY77	Unknown	1985 to 1995	High-cost components; energy storage	1
Geothermal	Geyser - proven; other types - pilot; $100, FY77	200	Geyser - present; others - 1980's	Drilling, well completion, effluent, corrosion	2 to 3
Wind (large)	Demonstration, $15, FY77	.5	Early 1980's	Site selection, component cost	2
Hydroelectric	Proven, $0	40	Present	Site location and acquisition	3 to 5
Ocean thermal	Conceptual, $8.2, FY77	160	1985 to 1990	Heat-exchanger fouling, remote location, high capital cost	1
SPS	Conceptual	5000	1995 (Scenario B)	High costs, transportation, solar conversion, pilot demonstration	6 (Scenario B)

[a]Percentage of electricity.
[b]150 000 tons/day.
[c]High-temperature gas-cooled reactor.

be generated by renewable energy sources, even after the 23 years of development between now and the year 2000. The 5 to 6 percent does not include SPS, that could provide another approximately 6 percent in the year 2000 if implemented per JSC scenario B (section III).

B. Cost Comparisons

Figure XI-1 shows a summary comparison of the cost of electricity for the various alternatives investigated. The solid bars represent the range of actual and estimated costs at the bus bar (transmission and distribution costs not included), expressed in 1976 dollars. The actual costs are associated with the conventional systems (natural gas, oil, coal, nuclear LWR, and hydroelectric). In the case of the advanced systems, the costs were derived from available data sources that tend to be advocates of the particular technology. Therefore, to some extent, the low ends of cost ranges probably reflect considerable optimism with respect to realizable costs.

No attempt was made to "adjust" the figures through critical analysis, because of the difficulty in obtaining the required detailed cost parameters used by the individual data sources.

The lower horizontal line marked "Year 1976" is the upper limit of the average coal-fired power generation (26 mills/kWh), and it probably represents the upper limit of the 1976 competitive range. The fuel-cost portion of the 26 mills/kWh is 11 mills/kWh, which corresponds to $1.10 per million Btu or $22 per ton of coal. In some parts of the country, coal costs as much as $35 per ton in large quantities.

The dashed vertical bars shown in figure XI-1 represent the year 2000 cost of electricity for the various alternatives. The projections were obtained by applying a general inflation factor of 4 percent compounded annually and a fuel cost inflation factor of 6 percent compounded annually to the 1976 costs. With these inflation factors applied, the year 2000 upper limit cost of electricity for coal-fired systems increases to about 82 mills/kWh.

It should be noted that the hydroelectric, wind, and geothermal power are very low cost in comparison with the other systems. These systems do not use fuel and, therefore, are not subject to the differential inflation assumed. Also, the geothermal costs are based on optimistic development of geothermal resources. The existing geothermal geyser powerplants (northern California) have low power-production costs, which probably bias the geothermal cost estimates to the low side. Hydroelectric power is generally low-cost power, where available because (1) no fuel charge exists, (2) capital cost, although relatively high, is written off over very long plant lifetimes, and (3) maintenance costs are relatively low. The wind power estimates are based on operation in the "fuel saver" mode in conjunction with some other type of powerplant, to provide continuous service. No storage is used; therefore, the system is not a baseload plant.

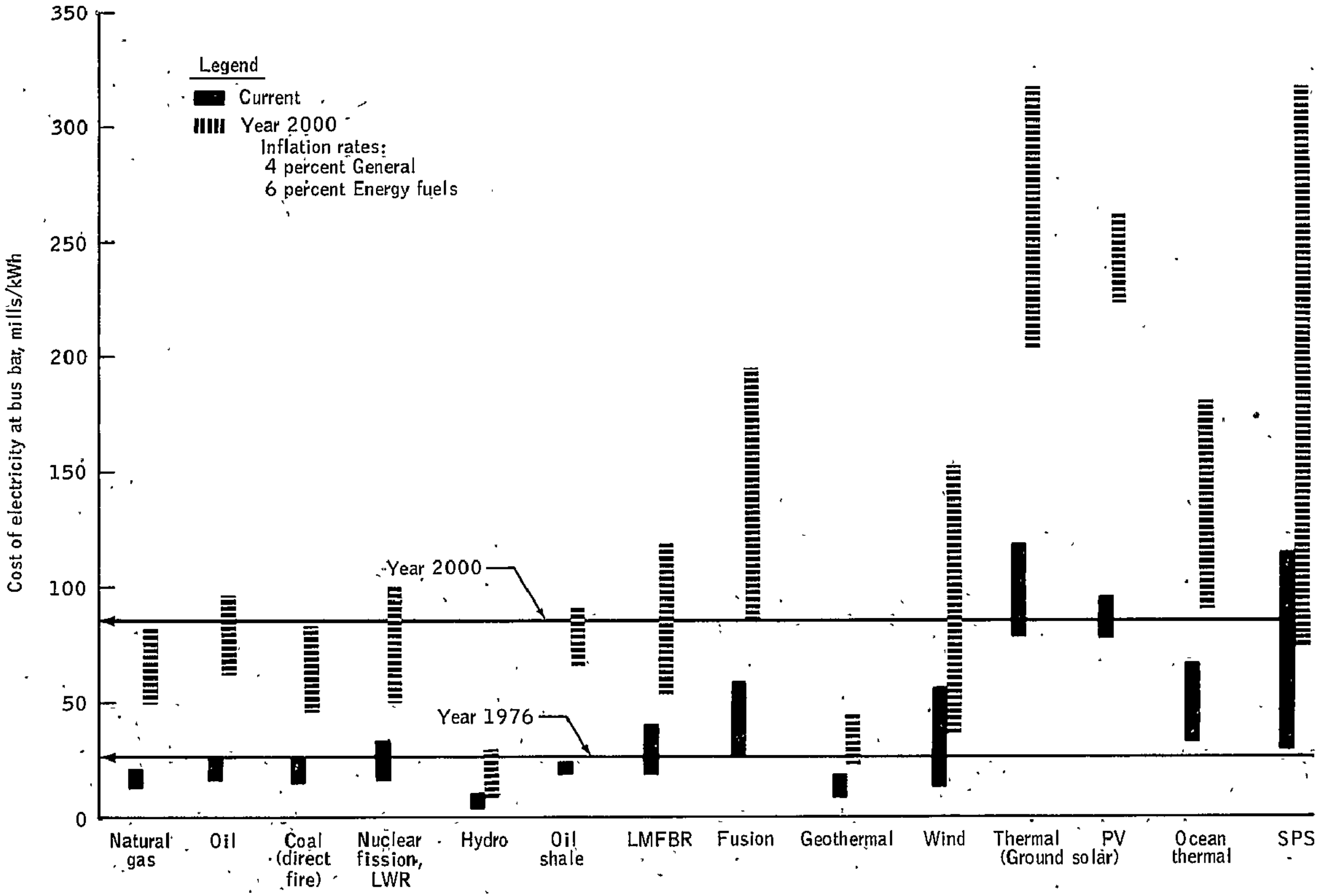


Figure XI-1.- Power-generation costs, showing various presently used and potential systems in relation to present and projected costs.

The ground solar-electric systems shown are for thermal and photovoltaic conversion concepts derived by JSC for purposes of cost comparison. This was necessary because no complete system cost could be found in the literature. The concepts are, however, based on subsystem technology currently under development. A "power tower" concept is used with a combination fuel-cell and electrolysis-cell energy-storage system, to provide baseload capability. The energy is stored in the form of cryogenic hydrogen (60 hours capacity). The photovoltaic system uses the same type of storage system, and its capital cost assumes the use of solar cells at $300 per peak kilowatt. The plant-site location assumed was southwestern United States, with an average annual solar insolation of 2500 kWh/m^2 (direct and diffuse) for the photovoltaic system and 2641 kWh/m^2 (direct only) for the Sun-tracking solar thermal concept.

The year 2000 startup SPS cost range, based on the previously cited inflation factor, is 74 to 294 mills/kWh. The lower range is comparable (actually less than) the coal system cost in 2000, and it is competitive with nuclear (LWR and LMFBR). In its higher estimated cost range, the SPS is comparable to nuclear fusion, terrestrial solar electric, and ocean thermal systems.

Figure XI-2 is shown to illustrate the effect of fuel cost on cost of electricity for coal, nuclear, and oil-fired systems. The cost curves shown do not include inflation. The nominal, maximum, and minimum SPS generation costs are shown for reference; and, as indicated, they would be independent of fuel costs.

C. Environmental Considerations

Table XI-3 shows a comparison of the power-system alternatives in terms of the environmental factors of land use, water consumption, air pollution (with abatement), waste storage or disposal requirements, and other factors. The values shown are for a 5000-MW (5 GW) powerplant capacity.

The range of land use for the natural gas, oil, coal, and nuclear systems reflects differences in cooling requirements, primarily. The larger land requirement is associated with a system that uses a dedicated cooling pond (or lake) for waste-heat rejection. The land use factor includes the steady-state land requirement for surface mining operations, accounting for a 10-year reclamation cycle. The land requirement for wind power is based on an approximation of 40 MW/1.6 km^2 in the Midwest. The land requirement for the SPS is based on a 10- by 14-kilometer rectenna for a 5-GW output.

The water consumption values are for cooling and process requirements. The cooling mode assumed was wet cooling towers, where the water is actually lost through evaporation and drift. For once-through cooling systems, the cooling water flow requirements would be higher than indicated.

The air pollution values shown are for steady-state operation. The one exception is the SPS, where the air pollution values shown originate from rocket propulsion through the atmosphere and apply to the satellite

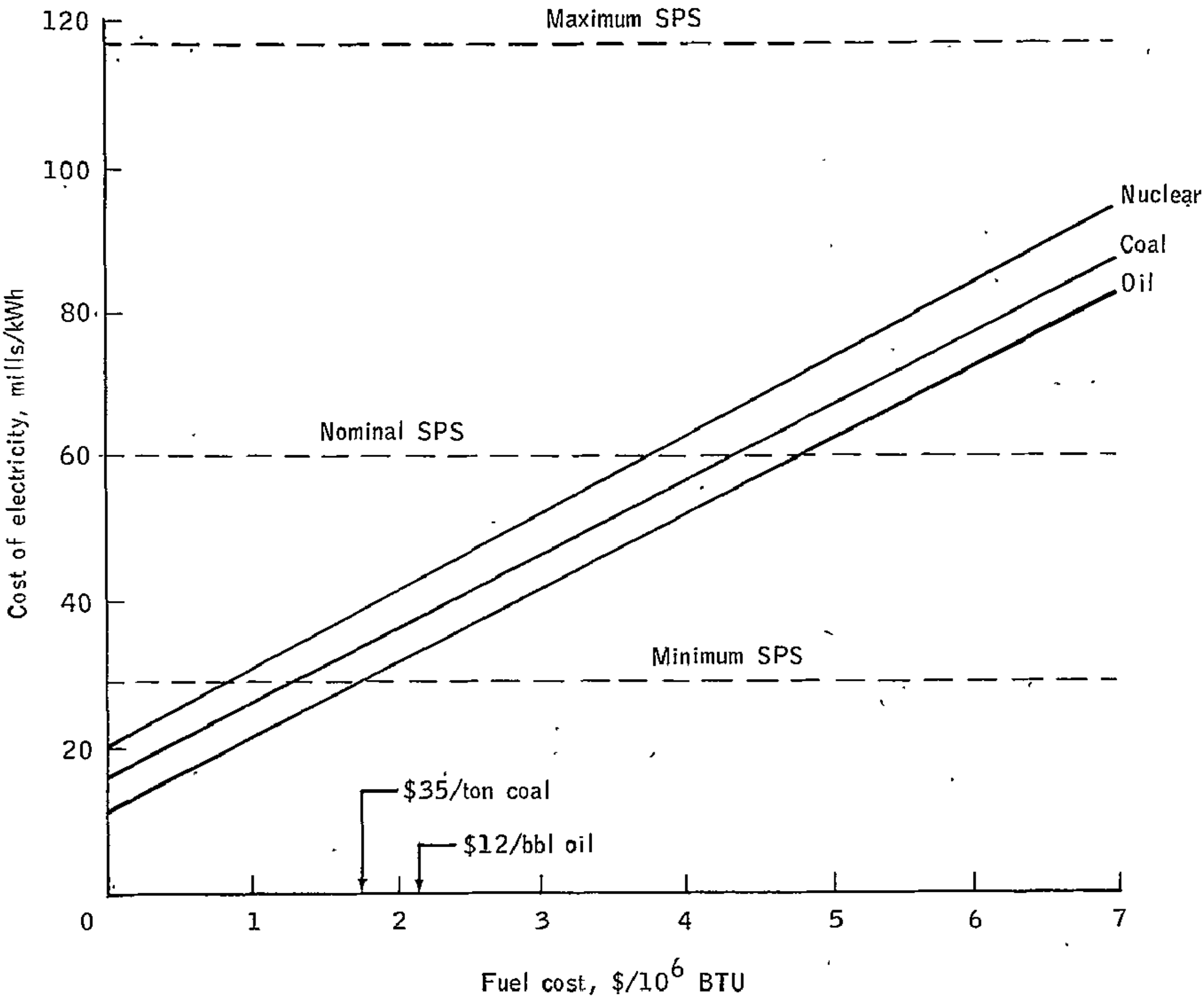


Figure XI-2.- Cost of electricity versus fuel cost showing SPS costs relative to nuclear, coal, and oil-fired systems.

construction period only. The nuclear systems have various levels of radioactive substances emitted to the air, as indicated in the table in terms of curies (Ci) per year.

D. Summary Remarks

On the basis of the preceding data and discussion, several general conclusions may be made relative to SPS, as follows.

1. To the depth studied, the SPS is potentially cost competitive with alternative sources in the year 2000 time period.

2. Inflation of fuel costs at a higher than general inflation rate improves the competitive position of SPS relative to fuel-using systems; i.e., coal, nuclear LWR, oil/gas.

TABLE XI-3.- 5000-MW PLANT ENVIRONMENTAL FACTORS

System	Land use, km^2	Water consumption, 10^9 gal/yr		Air pollution with abatement				Waste storage/disposal	Other factors
		Cooling	process	SO_x 10^3 tons/yr	NO_x 10^3 tons/yr	Particles, 10^3 tons/yr	10^3 Ci/yr		
Natural gas	4 to 31	13	1.2	0.1	55	2.1	0	Small	
Oil	17 to 43	13	1.5	235	105	8	0	Small	
Coal (direct fire with stack gas cleanup)	21 to 45	13	1.5	80	100	16	0	2 to 5×10^6 tons/yr, disposal	Fuel supply by rail undesirable
Oil shale	16 to 38	13	15 to 45	.8	1.2	5	0	125×10^6 tons/yr, disposal	85 percent of ore concentrated in small region
Fission:									
LWR	5 to 38	18	1	3.5	4	.3	7 to 50	Storage 65 000 to 180 000 ft^3/yr	
LMFBR	5 to 30	14	1	Small	Small	Small	.3 to .7	Storage 80 000 to 210 000 ft^3/yr	
Fusion	Unknown	13	Unknown	Small	Small	Small	4 to 40	Unknown	
Geothermal	110	0 to 30	Unknown	(a)	(a)	(a)	0	12 to 200×10^6 tons/yr, waste water disposal	Land-subsidence questions
Wind	348	0	0	0	0	0	0	0	Unfavorable aesthetics - many towers
Ground solar:									
Thermal	142	13	0	0	0	0	0	0	
Photovoltaic	465	0	0	0	0	0	0	0	
Hydroelectric	574	0	0	0	0	0	0	0	Recreation, flood control, and other benefits
Ocean thermal	Small	0	0	0	0	0	0	0	
Satellite solar power	110	0	0	4[b]	2[b]	Small[b]	0	0	

[a] H_2S, 200 000 tons/yr; NH_3, 270 000 tons/yr.
[b] Launch year only.

3. The SPS offers environmental advantages of very low air pollution, no major cooling or process water requirements, and no significant residual material for storage and/or disposal. Questions regarding microwave effects on the environment require further analysis for resolution.

4. A large mix of power system technologies will continue to be used in the future, even though sources such as oil and gas will be curtailed. No single source will dominate the power-generation utility field, although it appears that about 75 percent of the power will be produced by coal and nuclear energy at the turn of the century.

5. SPS land use for rectenna siting is up to 5 times less than land requirements for other renewable energy source systems (ground solar electric, hydroelectric, etc.) for equivalent power production. SPS would require 2 to 5 times more land than an equivalent coal-fired plant, based on an optimistic 10-year recycle time for strip-mined land reclamation.

National Aeronautics and
Space Administration

Distribution list

Lyndon B. Johnson Space Center
Houston, Texas 77058

JSC

AA	Office of the Director
AT	Technical Planning Ofc.
BC2	Program Procurement Div.
BV2 LS	Schedule Planning and Integration Ofc.
CA	Flight Operations Dir.
CB	Astronaut Ofc.
DA	Life Sciences Dir.
EA	Engineering and Development Dir.
EA2	Assistant Dir. for Program Support
EA4	Assistant Dir. for Program Development
EA7	Technical Assistant for Technology
EC	Crew Systems Div.
ED	Experiment Systems Div.
EE	Tracking and Communications Development Div.
EG	Control Systems Development Div.
EJ	Avionics Systems Engineering Div.
EL	Space Environment Test Div.
EP	Propulsion and Power Div.
ER	Future Programs Ofc.
ES	Structures and Mechanics Div.
EW	Spacecraft Design Div.
EX	Engineering Analysis Div.
EZ	Systems Evaluation Ofc.
FA	Data Systems and Analysis Dir.
FM2	Flight Planning Br.
FM15	Technology Development Ofc.
JA	Center Operations Dir.
JH	Technical Services Div.
NA	Safety, Reliability and Quality Assurance Dir.
PA	Shuttle Payload Integration and Development Program Ofc.
RA	White Sands
SA	Space and Life Sciences Dir.
SC	Science Payloads Div
SN	Lunar and Planetary Sciences Div.
WA	Program Operations Ofc.

NASA Headquarters

ECF	S. Fordyce
N	R. Ginter
NT	R. LaRock
	H. Calahan
	S. Manson
MT	J. Disher
MTE	T. Hagler
MTG	M. Savage

ARC

D	Director

DFRC
Director

GSFC

100	Director

JPL

100	Director
238	R. Dickinson
528	
277	R. Caputo
202	

KSC

CD	Director

LRC

0100	Director
364	C. Tynan
246E	A. Guastaferra
190	E. Kruszewski

LeRC

0100	Director
49-4	J. Ward
	R. Schuh
100-1	F. Teren

MSFC

DA01	Director
PA01	J. Murphy
PS01	C. Guttman (5)
PD01	K. Fikes

WFC
Manager

Energy Research and Development Administration (ERDA)
20 Massachusetts Avenue
Washington, DC 20545

Solar
H. Marvin
F. Koomanoff (5)
J. Madewell

ASGA
D. Beattie

BER
M. Minthorn

DTO
H. Wasson